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PREDICTING THE PERFORMANCE OF SOLAR ENERGY SYSTEMS.(U)
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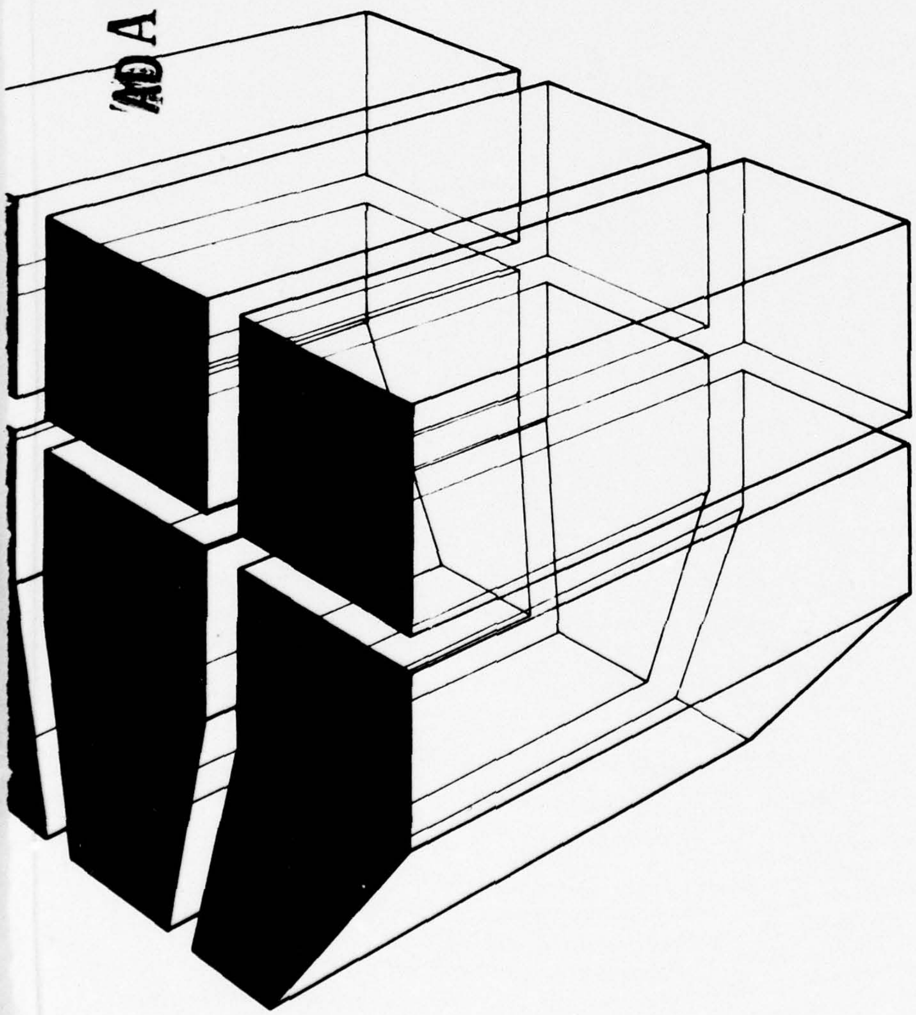
PREDICTING THE PERFORMANCE OF SOLAR ENERGY SYSTEMS



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This report presents a method for making an energy and life-cycle cost analysis of solar energy systems. A graphical method is presented for predicting the performance of solar domestic hot water systems, solar heating systems, and solar heating and cooling systems. Methods for selecting the optimum collector area based on life-cycle cost and for systematically making detailed design calculations using the Building

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Block 20 continued.

Loads Analysis and System Thermodynamics (BLAST) computer simulation program are also presented. Practical considerations for solar system designs are discussed.

The methods presented provide the required accuracy for both initial evaluations and final design calculations. Examples are provided throughout the text to aid in using the methods described.

FOREWORD

This work was performed for the Directorate of Military Construction, Office of the Chief of Engineers (OCE), under Project 4A763734DT08, "Military Construction Engineering Development"; Task 06, "Energy Conservation"; Work Unit 001, "Solar Energy for Heating and Cooling of Buildings." Mr. S. Hiratsuka served as the OCE Technical Monitor.

This study was performed by the Energy Systems Branch (EPE), Energy and Power Division (EP), U.S. Army Construction Engineering Research Laboratory (CERL). Dr. D. Leverenz is Chief of EPE and Mr. R. G. Donaghy is Chief of EP.

Appreciation is expressed to Dr. D. M. Joncich of CERL for assistance in developing the examples and reviewing the methodologies, and Mr. S. Chen, also of CERL, for assistance in preparing the universal curves.

COL J. E. Hays is Commander and Director of CERL and Dr. L. R. Shaffer is Technical Director.

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PREDICTING THE PERFORMANCE OF SOLAR ENERGY SYSTEMS

1 INTRODUCTION

Background

The technical feasibility of heating and cooling buildings using flat-plate solar collectors has been established both in theory and practice. Although improvements in component and system design are forthcoming, one can approach solar heating and cooling technology with full confidence that a practical, reliable system can be constructed. The construction phase of solar systems requires little more skill than is presently required to install conventional heating and cooling systems; the design phase, however, is considerably more complex.

Sunlight is inherently an intermittent source of energy at the earth's surface. For this reason, solar energy systems for heating domestic hot water or for heating and cooling buildings are not and frequently cannot be designed to meet the full demands of the building or buildings being served. System design is therefore unconventional in that solar energy supplies some but not all of the building's energy requirements. The fundamental problem in analyzing solar energy systems is determination of the collector array area which will provide the greatest cost benefit in meeting the highest fraction of the building's energy load. In the past, because of the uncontrolled nature of solar energy, extensive and costly computer studies (taking into account hourly weather data from the site in question) have been required to evaluate proposed solar projects and to design solar energy systems. The tools used for these studies have generally been proprietary and thus not available to Corps of Engineers Districts. Those which have been available are extremely difficult to use and are not ready for general use by design engineers.

Hence, there is a basic need for a simple, convenient method for making the necessary design calculations and for assessing energy and life-cycle costs. In particular, simplified techniques for making a preliminary energy and life-cycle cost analysis are needed to minimize the number of expensive computer studies required. Where computer studies are required, user-oriented computer programs are necessary.

Objective

This work is part of a study to develop a straightforward procedure to allow District Engineers to perform an energy and life-cycle cost analysis and final design calculations for individual solar energy system applications. The procedure was to permit (1) preliminary solar energy system performance assessment from charts and graphs and (2) the computer-aided evaluations of solar energy system performance necessary for final design, and was to be applicable to water and air heating systems and water heating and cooling systems. The purpose of this report is to describe how to use the graphical and computer tools developed in response to the study objective.

Approach

The approach used in this research consisted of the following steps:

1. Develop a computer simulation program for analyzing the performance of solar energy systems.

2. Use the solar simulation program to determine the performance of typical solar systems in meeting predetermined hourly building loads at each of five sites in the continental United States using hourly incident radiation data.

3. Study the effects on solar system performance of varying solar system design parameters (including collector area, collector tilt angle, storage tank volume, and heat exchanger effectiveness).

4. Based on the results of the parametric studies, develop a graphical method for estimating solar system performance.[1]

5. Develop a user-oriented computer simulation program for making rigorous solar system performance calculations during the final design phases.[2]

6. Develop recommended procedures for using the graphical and computer simulation techniques

[1] D. C. Hittle, D. F. Holshouser, and G. N. Walton, ***Interim Feasibility Assessment Guidance for Solar Heating and Cooling of Army Buildings***, Technical Report E-91/ADA026588 (U.S. Army Construction Engineering Research Laboratory [CERL], 1976).

[2] ***Building Loads Analysis and System Thermodynamics (BLAST) Program: Users Manual***, Draft Technical Report (CERL, 1977); and ***Building Loads Analysis and System Thermodynamics (BLAST) Program: Reference Manual***, Draft Technical Report (CERL, 1977).

for making solar system energy and life-cycle cost analysis, and for optimizing solar system designs based on lowest system life-cycle cost. This report describes these procedures.

Organization of Report

Chapter 2 introduces the graphical method for computing expected performance of solar collector arrays, and Chapter 3 presents examples of its use. Chapter 4 describes a method for optimizing the solar energy system on the basis of life-cycle cost. Chapter 5 describes the computer-aided method for solar energy systems which is recommended for performing design calculations on larger projects. Chapter 6 outlines some practical considerations relevant to the application of solar technology.

2 THE UNIVERSAL SOLAR SYSTEM PERFORMANCE CURVE— A GRAPHICAL APPROACH

Introduction

During the development of a solar system simulation model and design methodology, the U.S. Army Construction Engineering Research Laboratory (CERL) performed several hundred solar system simulations for typical Army buildings in various parts of the country. Analysis of the solar system performance curves for these systems indicated that with proper normalization, the performance of a given solar system for the various buildings in all locations could be represented by a single universal performance curve.

Use of this curve requires calculation of building energy loads and compilation of on-site weather data. Once this information is available, the curve relates solar system performance to the collector array area. In order to apply the curve, however, an understanding of the following terms is required:

1. Annual or monthly incident solar radiation flux density, Q_c. This is the solar flux density on the tilted collector array in Btu/square foot/month or Btu/square foot/year (langleys/month or langleys/year). Note that solar data for a particular site are given in terms of horizontal radiation densities. Thus, these numbers must be corrected for the tilt angle of the collector array. The method for making these corrections is presented in the *Solar Radiation Data* section of this chapter.

2. Annual and monthly energy requirements, Q_L. For the purposes of the universal curve, the energy requirements are defined as the total thermal energy in the form of hot water required by the building's domestic hot water heating system, space heating system, or absorption chiller.

3. Percentage of energy requirements met by solar energy, ϱ. This term is the percentage of Q_L met by the solar energy system.

Figure 1 shows the form of the three universal curves presented in this report—one for domestic hot water heating only (shown in Figure 1), one for heating only (with or without domestic hot water heating), and one for heating and cooling.

The X axis is the solar system performance parameter, P_s, which is defined as the ratio of annual or monthly incident radiation on the collector array to the annual or monthly energy requirements of the building, as given by Eq 1:

$$P_s = \frac{Q_c A_c}{Q_L} \qquad \text{[Eq 1]}$$

where A_c = collector area.

The Y ordinate, ϱ, is the fraction of Q_L supplied by the collector system. For example, a 200-man barracks in Topeka, KS requires 1.73×10^9 Btu (1.83×10^9 kJ) of energy annually to heat hot water. Use of the universal curve permits determination of the percentage of the load which can be met by 2400 sq ft (223 m^2) of collectors tilted at 39 degrees.

The solar radiation flux density, Q_c, on a collector tilted at 39 degrees is 6.0×10^5 Btu/sq ft (5.9×10^4 kJ/m^2). (The method for obtaining solar flux density on a tilted surface is described in the *Solar Radiation Data* section.) From Eq 1, P_s = .83; from Figure 1, ϱ is .48. Thus, 2400 sq ft (223 m^2) of collector would meet 48 percent of the load; i.e., the collector array would supply (.48) (1.73×10^9 Btu) = 8.3×10^8 Btu (8.8×10^8 kJ), and the auxiliary system would have to supply 9×10^8 Btu (9.5×10^8 kJ) with a conventional hot water heating system.

If the efficiency of the auxiliary energy supply system (an oil boiler, for example) is 80 percent, the solar energy system would save 10.4×10^9 Btu (10.97×10^9 kJ) of fuel energy. If the heating value of oil is 150,000 Btu/gal (41 809 kJ/ℓ) at a cost of \$0.40/gal (\$0.11/ℓ), the annual dollar savings would

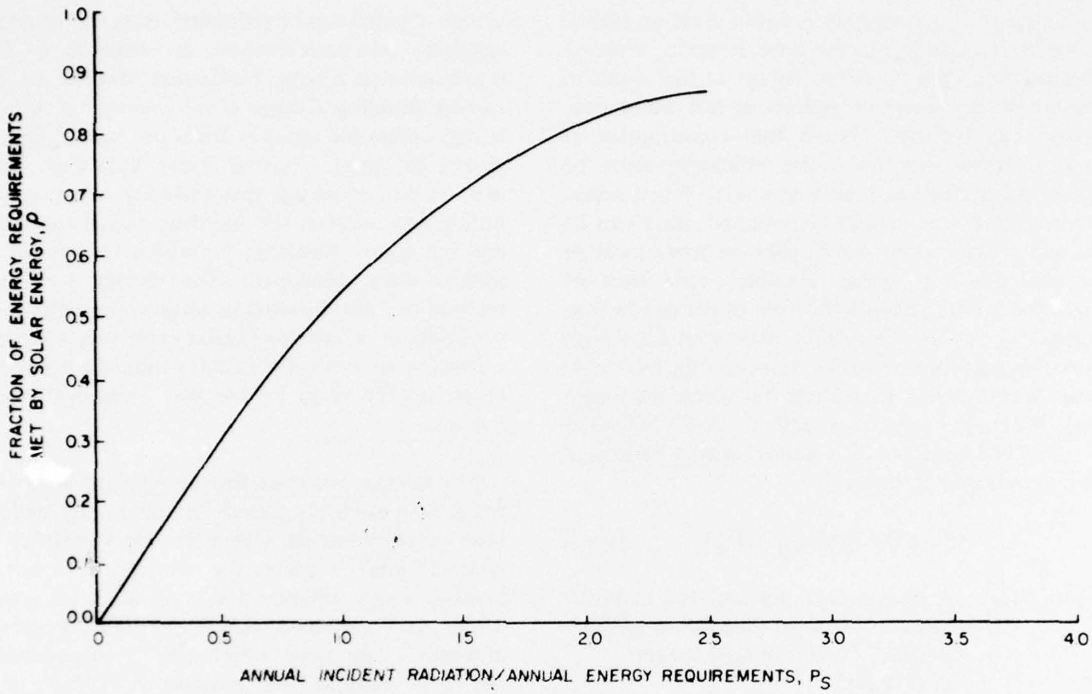

Figure 1. Universal curve for hot water heating with solar energy.

be $27,700. This savings could be used to offset the capital cost of the solar system. With this information, a life-cycle cost analysis for this candidate solar system can be made. The procedure can be repeated for different collector areas until the collector area giving the maximum cost benefit is found.

It should be pointed out that the universal curve contains several assumptions. First, a single-cover flat-plate collector with an emissivity of 0.10 and an absorptivity of 0.90 was used as the reference collector to develop the universal curve. (A method for adjusting the collector area for collector types other than the reference collector is presented in Chapter 3.) Second, the storage tank was assumed to hold 16 lb of water per square foot of collector (78 kg/m^2 or about 2 gal/sq ft). This was found to be near optimum in CERL simulation studies. Variations in tank volume can be evaluated in the final design phase using the computer simulation model (see Chapter 5).

Obtaining Required Input Information

As the example in the previous section shows, two sets of input information in addition to collector area are required to use the universal curve: the thermal energy demand, Q_L, and the radiation flux density, Q_c. The following sections describe how this information can be obtained.

Energy Consumption Data

The type of data required to determine Q_L and the sources of that data depend on the type of system being considered. Since solar energy systems produce thermal energy in the form of hot water (or hot air in the case of hot air solar heating systems), consumption or energy requirements in any other terms —such as kilowatt hours supplied to or required by a centrifugal chiller, Btu's of chilled water required, gallons of oil or cubic feet of gas supplied to a boiler, or gallons of hot water used—must be converted to thermal energy in the form of hot water (or hot air if a hot air system is used). This usually requires taking into account the efficiency of conversion equipment as well as the appropriate conversion factors. Determination of Q_L for the three types of systems is described below.

Solar Domestic Hot Water System. To use the universal curve for domestic hot water systems, the annual energy needed for heating the hot water is required. The best source of information is metered

data from the building in question or from an identical or similar building at the same location. Metered consumption data for either energy or fuel input to the hot water heater or gallons of hot water consumed can be used. When fuel consumption is known, corrections for boiler efficiency must be taken into account as discussed above. When actual consumption data cannot be obtained, data can be derived from various handbooks or from local or national plumbing codes. However, care must be exercised in using data in the form of per capita consumption, as they are usually developed for design purposes and thus are often more closely related to peak demand than to average hot water consumption. Whichever method is used, if annual hot water demand is determined, the annual energy consumption is obtained from Eq 2:

$$Q_L = DwCp\,(T_{out} - T_{in}) \qquad \text{[Eq 2]}$$

where Q_L = annual energy consumption in Btu(J)
D = annual hot water demand in gal(ℓ)
w = density of water = 8.33 lb/gal (1.00 kg/ℓ)
C_p = specific heat of water = 1 Btu/1bm °F (4.1868 kJ/kg °K)
T_{out} = temperature of hot water supply in °F (°C)
T_{in} = temperature of supply water in °F (°C)

Solar Heating Systems. Since the length of the heating season varies significantly from site to site, the universal curve for solar heating systems (liquid or air) must be used on a monthly basis. This in turn requires that the monthly energy demand for heating be obtained.

Again, the best source of data for estimating the amount of heat energy required for a particular building or set of buildings is measured data for the building in question or for similar or identical buildings at the same location. These data may only be available in terms of the amount of fuel oil used per month or the amount of gas consumed in heating the particular building or buildings. If so, the fuel consumption data must be adjusted to account for the efficiency of the boiler or furnace supplying the heat to the space. Typically, solar heating systems include both heating the building and the domestic hot water for the building. This can be accounted for in the energy requirement by adding the monthly domestic hot water load to the heating load.

If measured data for the building being considered are not available, the building's heating energy demand can be estimated using one of several methods. One such method, described in a CERL report entitled *Energy Utilization Method for Predicting Building Energy Use,*[3] provides a monthly energy utilization index in Btu's per square foot per month for several typical Army buildings and a method for adjusting this estimate based on the differences between the building being considered and the typical buildings for which the energy use indices were developed. The energy use index method can also be used in conjunction with measured data for a building similar to the one being considered by adjusting the data for the similar building based on the ratio of the two buildings' energy indices.

The Carrier Rational Energy Analysis Procedure (REAP)[4] is another method for calculating building heating requirements. This method is a modified bin method[5] which requires the calculation of heating loads at several different design points of the system. These loads combined with frequency of occurrence of weather conditions, which can be obtained from Air Force Manual 88-8,[6] provide an estimate of the monthly energy requirements for heating.

A fourth method requires application of the Building Loads Analysis and System Thermodynamics (BLAST) computer simulation program to predict the monthly heat energy demands. Use of this program, which is described in the program user's manual,[7] requires an hourly weather data tape.

Monthly energy consumption for domestic hot water heating, which is generally included in a solar heating system, can be determined by applying the methods described in the preceding section on a monthly basis. It should be noted that measured data often have domestic hot water and space heating combined.

[3] L. M. Windingland and D. C. Hittle, *Energy Utilization Index, Method for Predicting Building Energy Use,* Draft Technical Report (CERL, 1977).

[4] *Rational Energy Analysis Procedure (REAP)* (Carrier Air Conditioning Company, undated).

[5] *ASHRAE Handbook of Fundamentals* (American Society of Heating, Refrigerating and Air Conditioning Engineers [ASHRAE], 1972).

[6] *Engineering Weather Data,* AFM 88-8, Chapter 6 (Department of the Air Force, 1967).

[7] *Building Loads Analysis and System Thermodynamics (BLAST) Program: Users Manual,* Draft Technical Report (CERL, 1977).

Design day calculations alone **cannot** be used to obtain heating loads, since they provide peak energy demands rather than the average demand required for estimating monthly energy consumption.

Solar Heating and Cooling Systems. The universal curve for solar heating and cooling systems is an annual curve, since there is a year-round demand for energy. Thus, the annual energy is needed. The annual energy required is the sum of the heating and cooling energy requirements plus the domestic hot water heating energy requirement if it is to be included in the system.

The annual energy required for heating and cooling is again best determined from measured data for the building in question or a similar or identical building at the same location. In determining the energy required for cooling, attention must be given to the differences in the coefficients of performance (COP) of the various chillers involved. For example, if measuring the consumption of electricity for a conventional chiller in the building indicates that 1,000,000 kWh are used annually, then this number must first be converted to Btu's by multiplying by 3412, giving 3.41×10^9 Btu (or converted to kilojoules by multiplying by 3600, giving 3.60×10^9 kJ), and then multiplied by the centrifugal chiller's mean COP. If the mean COP is 4, 13.6×10^9 Btu/yr (14.3×10^9 kJ/yr) are required to be delivered by the chiller to the cooling system. This chilled water demand, when divided by the COP of a solar energy system's absorption chiller (say .65) indicates that 21.0×10^9 Btu (22.2×10^9 kJ) must be supplied to the absorption chiller to meet the annual energy required for cooling. Since heating and cooling systems may also include domestic hot water heating, total demand for heat energy for heating domestic hot water can be summed with the total demand for heating and added to the annual demand for cooling energy in order to determine the annual building energy requirement, Q_L.

If measured consumption data are not available, the energy use index method, REAP method, or BLAST simulation program described in the previous section can be used to determine annual heating and cooling loads.

Solar Radiation Data

The tilt angle of the collector plate greatly affects the amount of solar radiation striking the surface of the plate. Most measured and reported data are for solar radiation striking a horizontal surface. This section describes where to obtain this information and how to correct it for tilted collector arrays.

Average solar radiation data for many sites around the country are published in the National Oceanic and Atmospheric Administration (NOAA) *Climatic Atlas of the United States.* Annual and monthly solar radiation maps from this document are reproduced in Appendix A. Since the radiation values on these maps are given in daily means, the annual and monthly values are obtained by multiplying by the number of days in the year or month, depending on the map being used.

The *Climatic Atlas of the United States* also contains tabulated summaries of radiation data for specific sites. More detailed summaries are frequently available from NOAA or from local weather services or state agencies. Data for the particular site in question should be obtained, if possible, since incident solar radiation frequently varies substantially over relatively small geographical distances. This is particularly true in coastal regions and in regions near mountains, where local climatological variations are severe.

Once the collector tilt angle is known, the radiation flux density on the tilted collector surface can be determined from horizontal radiation data. Fortunately, there is an optimum collector tilt angle (measured from horizontal) for each type of system. For heating and cooling systems, this optimum tilt angle, ϑ_c, is roughly the location latitude minus 10 degrees; for heating-only systems, it is roughly the latitude plus 10 degrees; and for domestic hot water systems, it is roughly equal to the latitude. These angles provide for collection of the greatest amount of solar energy in each application. Variations of ±5 degrees affect performance only slightly. In all cases the optimum azimuth angle is due south and again slight deviations from due south (±10 degrees) do not significantly reduce system performance.

Once the optimum tilt angle has been determined, the annual radiation flux density, Q_c, on the optimally tilted surface can be estimated from Eq 3:

$$Q_c = KH_\vartheta \qquad \text{[Eq 3]}$$

where K = a correction factor depending on the collector tilt

H_ϑ = the annual or monthly radiation flux density on a horizontal surface (Btu/sq ft or J/m²).

For solar systems for which annual solar radiation data are used (i.e., heating and cooling or domestic hot water), the correction factor, K, is given approximately by

$$K = \frac{\cos(\vartheta_L - 7 - \vartheta_c)}{\cos(\vartheta_L - 7)} \qquad \text{[Eq 4]}$$

where ϑ_L = the latitude in degrees
ϑ_c = the optimum angle from the horizontal in degrees.

Eq 4 is an empirically derived equation based on the results of simulation studies and is valid only for near-optimum collector tilt angles and annual solar radiation data.

For solar heating applications, where monthly radiation figures must be used, the correction factor may not be expressed in closed form. In this case, K must be determined from Table 1, which gives monthly values of this correction factor for four different latitudes. Table 1 is valid only for optimum collector tilt angles.

Table 1

Monthly Correction Factors (K) for Heating-Only Systems (for collector tilt equal to latitude plus 10 degrees)

	Latitude			
Month	**30°**	**35°**	**40°**	**45°**
Jan	1.64	1.84	2.12	2.49
Feb	1.42	1.55	1.71	1.93
Mar	1.18	1.25	1.33	1.44
Apr	.97	1.00	1.03	1.07
May	.84	.84	.85	.87
Jun	.78	.78	.78	.78
Jul	.80	.80	.80	.81
Aug	.90	.91	.93	.96
Sep	1.07	1.11	1.17	1.24
Oct	1.29	1.40	1.51	1.66
Nov	1.54	1.70	1.93	2.23
Dec	1.70	1.93	2.24	2.64

Recalling the example on page 8, the annual radiation for Topeka, KS was found as follows: the annual radiation level on a horizontal surface obtained from Figure A1 is 380 langleys/day. The latitude, ϑ_L (also from Figure A1), is 39. Using Eqs 3 and 4, Q_c can be found.

$$Q_c = KH_\vartheta = \frac{\cos(\vartheta_L - 7 - \vartheta_c)}{\cos(\vartheta_L - 7)} H_\vartheta$$

$$Q_c = \frac{\cos(39 - 7 - 39)}{\cos(39 - 7)} \left(\frac{380 \text{ langleys}}{\text{day}}\right)$$

$$\left(\frac{365 \text{ day}}{\text{yr}}\right)\left(\frac{3.69 \text{ Btu}}{\text{sq ft-langley}}\right)$$

$$Q_c = 6.0 \times 10^5 \text{ Btu/sq ft/yr}$$
$$(6.8 \times 10^6 \text{ kJ/m}^2\text{/yr})$$

As an example of applying the monthly correction factor used for heating-only systems, find the solar radiation for January in Topeka, KS. From Table 1, K is estimated by extrapolation between 35 degrees and 40 degrees latitude for January. Thus

$$K = 1.84 + \left(\frac{2.12 - 1.84}{40° - 35°}\right) \times 4°$$

$$K = 2.06$$

From Figure A2, the mean daily horizontal radiation is 190 langleys. Hence,

$$H_\vartheta = \left(\frac{190 \text{ langleys}}{\text{day}}\right)\left(\frac{31 \text{ days}}{\text{mo}}\right)\left(\frac{3.69 \text{ Btu}}{\text{sq ft-langley}}\right)$$

$$H_\vartheta = 2.2 \times 10^4 \text{ Btu/sq ft/mo } (2.5 \times 10^6 \text{ kJ/m}^2\text{/mo})$$

Thus,

$$Q_c = KH_\vartheta = 4.5 \times 10^4 \text{ Btu/sq ft/mo}$$
$$(5.1 \times 10^5 \text{ kJ/m}^2\text{/mo})$$

3 ESTIMATING SOLAR SYSTEM PERFORMANCE

General

In determining optimal collector area and making the energy and life-cycle cost analysis, a life-cycle cost comparison between a conventional system and the solar energy system for various collector areas is made. A critical step in this analysis is determination of the solar system performance to find out how much of the energy requirement is met by solar energy and how much is met by auxiliary heat for a given size collector array. In order to make this determination, the universal curves are used.

Analyzing a given solar system performance requires the following steps:

1. Determine the annual or monthly energy requirement, Q_L, as described on pages 9-11.

2. Determine the annual or monthly solar radiation on the optimally tilted collector array, Q_c, for the location in question using the method described on pages 11-12.

3. Determine the solar system performance using the universal curve. Two methods can be used to accomplish this:

a. If a collector area, A_c, is assumed, then the annual or monthly solar system performance parameter, P_s, can be found from Eq 1:

$$P_s = \frac{Q_c A_c}{Q_L} \qquad \text{[Eq 1]}$$

From this value and the universal curve, the annual or monthly fraction of energy met by the solar system, ϱ, can be determined. Using this value in Eqs 5 and 6 yields the energy supplied by auxiliary heat, Q_{LA}, and the energy supplied by the solar system, Q_{LS}.

$$Q_{LS} = \varrho Q_L \qquad \text{[Eq 5]}$$

$$Q_{LA} = (1 - \varrho) Q_L \qquad \text{[Eq 6]}$$

If the analysis is for heating-only systems, the monthly Q_{LS} and Q_{LA} are obtained from Eqs 5 and 6 and must be summed to get the annual values required for determining optimal collector area and making the energy and life-cycle cost analysis as described in Chapter 4.

b. The universal curve can also indicate what collector area is required to meet a given fraction, ϱ, of the annual or monthly energy requirement. This information is useful in establishing a starting point for a solar system analysis. The collector area can be determined by using ϱ to find P_s from the universal curve. For P_s, the collector area can be found from:

$$A_c = \frac{P_s Q_L}{Q_c}$$

Again, annual or monthly Q_{LS} and Q_{LA} can be found from Eqs 5 and 6.

The next sections present the universal curves for the various systems and examples of how to use them.

Solar Domestic Hot Water Systems

Development of the universal curve for domestic hot water heating (Figure 1) assumed a uniform annual hot water demand. If the system being analyzed has a highly seasonal demand, this curve should not be used. The curve also was derived for a system which has an inlet water temperature of 55°F (13°C) and a supply temperature of 140°F (60°C), which are typical of hot water systems. The curve is valid, however, for small variations (±20°F [±11°C]) about these values.

The following example illustrates application of the procedure outlined above for solar domestic hot water heating.

Example 1:

Assume a barracks at Fort Hood, TX consumes 30 gal (114 ℓ) of hot water per day per person and the average occupancy for the year is 200 people. The collector area which will meet 50 percent of the load if the city supply water is 55°F (13°C) and the hot water system supplies 140°F (60°C) water can be determined in the following manner:

1. First determine Q_L, the annual energy required to heat the water. Eq 2 gives:

$$Q_L = DwCp(T_{out} - T_{in})$$

$$Q_L = \left(\frac{30 \text{ gal}}{\text{person-day}}\right)(200 \text{ persons})\left(\frac{365 \text{ days}}{\text{yr}}\right)$$

$$\left(\frac{8.33 \text{ lb}}{\text{gal}}\right)\left(\frac{1 \text{ Btu}}{\text{lb°F}}\right)(140°\text{F-}55°\text{F})$$

$$Q_L = 1.6 \times 10^9 \text{ Btu/yr } (1.7 \times 10^9 \text{ kJ/yr})$$

2. Estimate Q_c, the annual solar radiation on the array. From Eqs 3 and 4,

$$Q_c = \frac{\cos(\vartheta_L - 7 - \vartheta_c)}{\cos(\vartheta_L - 7)} H_\vartheta$$

From Figure A1, the mean daily horizontal solar radiation at this location is 445 langleys/day. Thus,

$$H_\vartheta = \left(\frac{445 \text{ langleys}}{\text{day}}\right)\left(\frac{365 \text{ days}}{\text{yr}}\right)\left(\frac{3.69 \text{ Btu}}{\text{sq ft-langley}}\right)$$

$$= 6.0 \times 10^5 \text{ Btu/sq ft/yr } (6.8 \times 10^6 \text{ kJ/m}^2\text{/yr})$$

Also from Figure A1, ϑ_L is 33 degrees (latitude of

Fort Hood, TX). Since this is a domestic hot water system, the optimum tilt angle, ϑ_c, for hot water is equal to ϑ_L (33 degrees). Thus,

$$Q_c = 6.6 \times 10^5 \text{ Btu/sq ft/yr } (7.5 \times 10^6 \text{ kJ/m}^2\text{/yr})$$

3. Use the universal curve to estimate the solar performance. To meet 50 percent of the load, ϱ is .5. From Figure 1 (for ϱ equal to .5) ϱ_s is .85. The required collector area can now be found from Eq 1.

$$A_c = \frac{P_s Q_L}{Q_c} = \frac{(.85)(1.6 \times 10^9 \text{ Btu/yr})}{(6.6 \times 10^5 \text{ Btu/sq ft-yr})}$$

$$= 2 \times 10^3 \text{ sq ft } (186 \text{ m}^2)$$

The area required to meet 50 percent of the annual domestic hot water load is 2000 sq ft (186 m^2).

Solar Heating and Cooling Systems

Figure 2 shows the universal curve for solar heating and cooling systems. Analysis of the system's performance proceeds exactly as described in the previous section for domestic hot water systems. The following example illustrates the application of the solar heating and cooling universal curve.

Example 2:

The following example is for an administrative building housing 300 people in Champaign, IL (latitude 42 degrees). The energy consumption data were taken from monthly utility billings. The steps in the analysis are as follows:

1. First determine Q_L, the annual energy requirement for heating and cooling.

a. For heating, power records indicate that for the months of October through June, 144 × 10^8 Btu (152 × 10^8 kJ) of gas were consumed for heating and domestic hot water. When multiplied by a boiler efficiency of .75, the building heating load is found to be 108 × 10^8 Btu (114 × 10^8 kJ).

b. For cooling, utility records show that for the months of April through November, 81 × 10^4 kWh (28 × 10^8 Btu [29.5 × 10^8 kJ]) were consumed by the centrifugal chiller. The chiller load was found by subtracting the average winter electrical load from the average summer electrical load to account for other, noncooling loads. Thus, chiller electrical load, when multiplied by the COP of the centrifugal chiller (found from manufacturer's literature to be 4), gives a cooling load for the building of 112 × 10^8

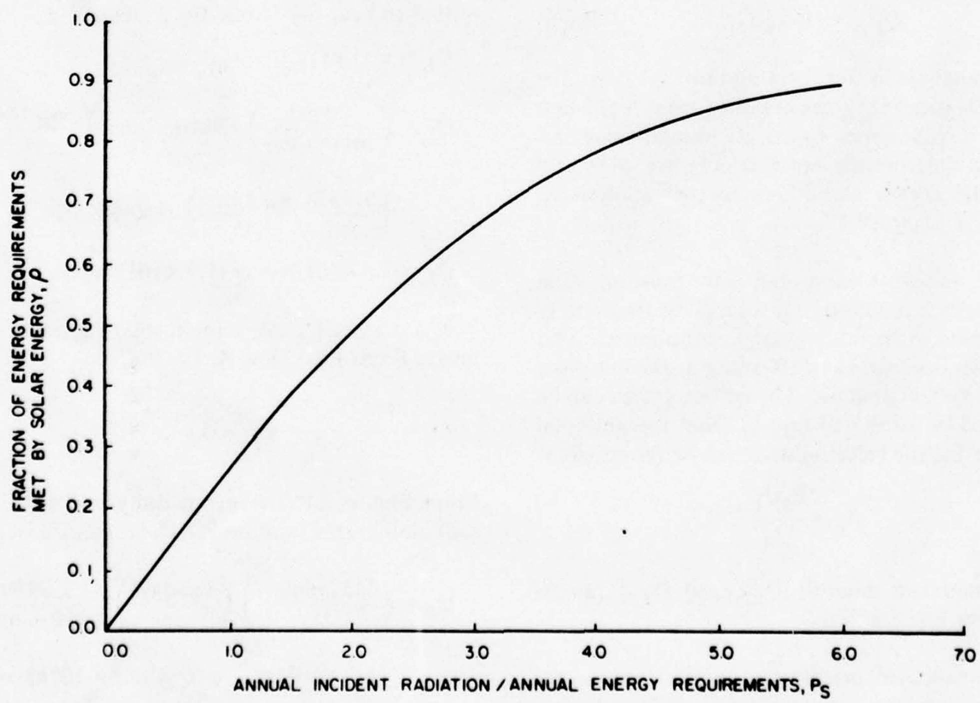

Figure 2. Universal curve for solar heating and cooling systems.

Btu (118×10^8 kJ). Dividing by the COP of the absorption chiller (.65) indicates that 172×10^8 Btu (181×10^8 kJ) must be supplied to the absorption chiller to meet the annual cooling energy demand.

Hence,

$$Q_L = 108 \times 10^8 \text{ Btu/yr} + 172 \times 10^8 \text{ Btu/yr}$$

$$Q_L = 280 \times 10^8 \text{ Btu/yr } (295 \times 10^8 \text{ kJ/yr})$$

2. Estimate the annual solar radiation, Q_c, on the optimally tilted collector array. From Eqs 3 and 4

$$Q_c = \frac{\cos(\vartheta_L - 7 - \vartheta_c)}{\cos(\vartheta_L - 7)} H_\vartheta$$

From Figure A1, the mean daily annual solar radiation for Champaign, IL is 355 langleys/day. Thus H_ϑ is

$$H_\vartheta = \frac{355 \text{ langleys}}{\text{day}} \quad \frac{365 \text{ days}}{\text{yr}} \quad \frac{3.69 \text{ Btu}}{\text{sq ft-langley}}$$

$$= 4.8 \times 10^5 \text{ Btu/sq ft/yr } (5.5 \times 10^6 \text{ kJ/m}^2\text{/yr})$$

since $\vartheta_L = 42$ degrees (the latitude of Champaign)

and $\vartheta_c = \vartheta_L - 10$ degrees $= 32$ degrees

(optimum collector tilt angle for heating and cooling)

Thus, $Q_c = 5.6 \times 10^5$ Btu/sq ft/yr (6.4×10^6 kJ/m²/yr)

3. Determine the solar system performance from the universal curve for heating and cooling (Figure 2) assuming a collector area of 50,000 sq ft (4645 m²). From Eq 1, P_s is given by

$$P_s = \frac{A_c Q_c}{Q_L} = \frac{(5 \times 10^4 \text{ sq ft})(5.6 \times 10^5 \text{ Btu/sq ft/yr})}{(280 \times 10^8 \text{ Btu/yr})}$$

$$P_s = 1.0$$

For $P_s = 1$, Figure 2 shows $\varrho = .26$.

Hence, roughly 26 percent of the building's annual energy requirement for heating and cooling can be supplied by the sun using 50,000 sq ft (4645 m²) of collectors for an annual energy savings of 78.4×10^8 Btu/yr (82.7×10^8 kJ/yr).

Solar Heating Systems

Figure 3 shows the universal curve for solar heating systems. Methods for using the curve are similar to those for the two previous systems, except the analysis is performed month by month.

Since the domestic hot water load for a heating system is small in comparison to the space heating requirements, it can be assumed that the total hot water load is met by solar energy during the non-heating season. This somewhat simplifies the calculations, in that the monthly analysis needs to be performed only for those months with significant space heating loads. The hot water energy requirements for the other months can be summed and added directly to Q_{LS}. The following example shows how this monthly analysis is accomplished for heating-only systems.

Example 3:

The administrative building of Example 2 was used in this example to determine what percent of the heating load could be met by the 50,000 sq ft (4645 m²) of collectors. Again the energy consumption data were taken from monthly utilities bills. The steps in the analysis are as follows:

1. Determine the monthly loads, Q_L, for the heating season.

Table 2 presents the building's natural gas consumption indicated by the monthly utility records. The values of Q_L in the table have been corrected for a boiler efficiency assumed as .75. Note that the 108×10^8 Btu/yr (114×10^8 kJ/yr) total load is the same as found in Example 2.

2. Estimate Q_c, the annual solar radiation on the optimally tilted collector array. From Eq 3

$$Q_c = KH_\vartheta$$

where H_ϑ and Q_c = monthly radiation values.

K = the correction factor from Table 1.

H_ϑ is obtained from the figures in Appendix A. Monthly values for Q_c are listed in Table 3.

3. Determine the solar system performance from the universal curve for heating only (Figure 3), assuming a collector area, A_c, of 50,000 sq ft (4645

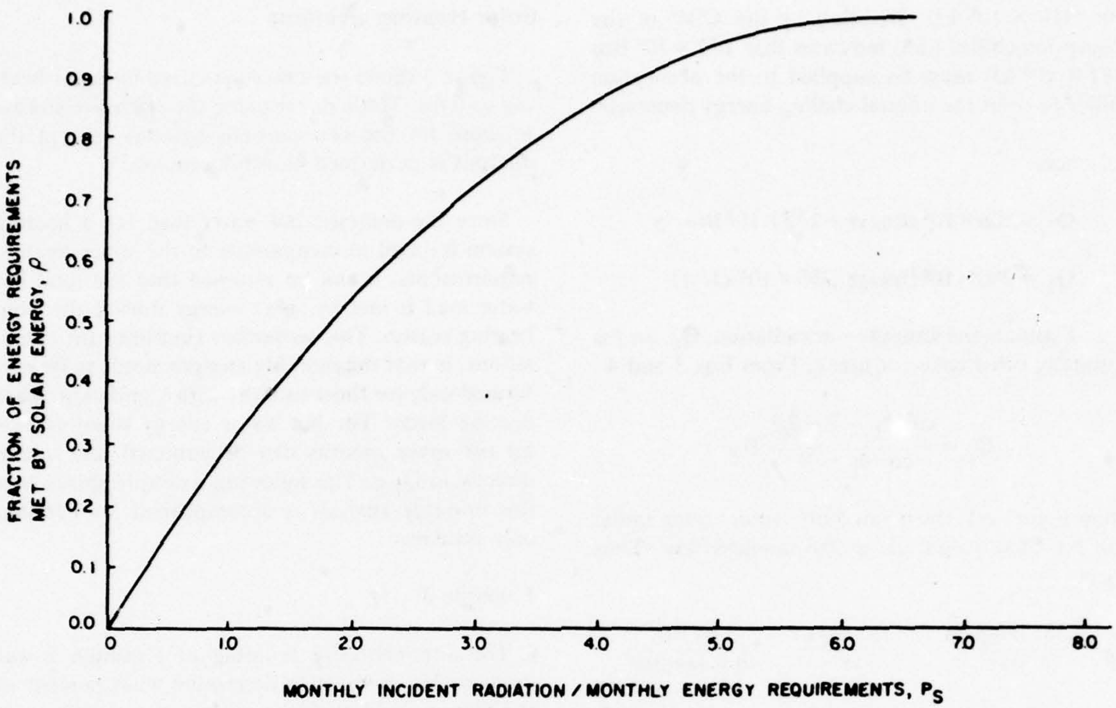

Figure 3. Universal curve for solar heating systems.

Table 2

Natural Gas Consumption for Example Administration Building

Month	Q_L (Heating) Btu × 10^8	(kJ × 10^8)	Q_L (Hot Water) Btu × 10^8	(kJ × 10^8)	Total Q_L Btu/mo × 10^8	(kJ/mo)
Oct	2.0	(2.1)	.6	(.6)	2.6	(2.7)
Nov	7.8	(8.2)	.6	(.6)	8.4	(8.9)
Dec	12.3	(13.0)	.6	(.6)	12.9	(13.6)
Jan	19.9	(21.0)	.6	(.6)	20.5	(21.6)
Feb	18.5	(19.5)	.6	(.6)	19.1	(20.2)
Mar	16.3	(17.2)	.6	(.6)	16.9	(17.8)
Apr	12.9	(13.6)	.6	(.6)	13.5	(14.2)
May	8.8	(9.3)	.6	(.6)	9.4	(9.9)
Jun	4.0	(4.2)	.6	(.6)	4.6	(4.9)
	102.5 × 10^8 Btu/yr	(108.1 × 10^8 kJ/yr)			107.9 × 10^8 Btu/yr	(113.8 × 10^8 kJ/yr)

m^2). From Eq 1, P_s for each month can be calculated from the monthly Q_L and Q_c presented in Tables 2 and 3.

From these values of P_s, the monthly values of ρ can then be obtained from the universal curve. Finally, from Eq 5, the load met by the solar system, Q_{LS}, can be found for each month (Table 4).

Table 3

Monthly Values for Q_c

Month	H_ϑ Langley/day	H_ϑ Btu/sq ft/mo (kJ/m²/mo)	K	Q_c Btu/sq ft/mo (kJ/m²/mo)
Oct	275	3.1 × 10^4 (3.5 × 10^5)	1.5	4.7 × 10^4 (5.3 × 10^5)
Nov	175	1.9 × 10^4 (2.2 × 10^5)	2.0	3.8 × 10^4 (4.3 × 10^5)
Dec	135	1.5 × 10^4 (1.7 × 10^5)	2.3	3.5 × 10^4 (4.0 × 10^5)
Jan	155	1.8 × 10^4 (2.0 × 10^5)	2.2	4.0 × 10^4 (4.5 × 10^5)
Feb	240	2.5 × 10^4 (2.8 × 10^5)	1.8	4.5 × 10^4 (5.1 × 10^5)
Mar	330	3.8 × 10^4 (4.3 × 10^5	1.3	4.9 × 10^4 (5.6 × 10^5)
Apr	400	4.4 × 10^4 (5.0 × 10^5)	1.0	4.4 × 10^4 (5.0 × 10^5)
May	510	5.8 × 10^4 (6.6 × 10^5)	.85	4.9 × 10^4 (5.6 × 10^5)
Jun	550	6.1 × 10^4 (6.9 × 10^5)	.78	4.8 × 10^4 (5.5 × 10^5)

Table 4

Monthly Values of ϱ and Q_{LS}

Month	Q_L Btu/mo (kJ/mo)	Q_c Btu/sq ft/mo (kJ/m²/mo)	P_s	ϱ	Q_{LS} Btu (kJ)
Oct	2.6×10^8 (2.7×10^8)	4.7×10^4 (5.3×10^5)	9.04	.99	2.6×10^8 (2.7×10^8)
Nov	8.4×10^8 (8.9×10^8)	3.8×10^4 (4.3×10^5)	2.26	.59	5.0×10^8 (5.2×10^8)
Dec	12.9×10^8 (13.6×10^8)	3.5×10^4 (4.0×10^5)	1.36	.39	5.0×10^8 (5.2×10^8)
Jan	20.5×10^8 (21.6×10^8)	4.0×10^4 (4.5×10^5)	.98	.29	5.9×10^8 (6.3×10^8)
Feb	19.1×10^8 (20.2×10^8)	4.5×10^4 (5.1×10^5)	1.18	.35	6.7×10^8 (7.0×10^8)
Mar	16.9×10^8 (17.8×10^8)	4.9×10^4 (5.6×10^5)	1.45	.41	6.9×10^8 (7.3×10^8)
Apr	13.5×10^8 (14.2×10^8)	4.4×10^4 (5.0×10^5)	1.63	.45	6.1×10^8 (6.5×10^8)
May	9.4×10^8 (9.9×10^8)	4.9×10^4 (5.6×10^5)	2.61	.65	6.1×10^8 (6.5×10^8)
Jun	4.6×10^8 (4.9×10^8)	4.8×10^4 (5.5×10^5)	5.22	.97	4.5×10^8 (4.7×10^8)
			Total	Q_{LS}	48.8×10^8 Btu (51.6×10^8 kJ)

The figures in Table 4 show that 48.8×10^8 Btu (51.6×10^8 kJ) of heating is supplied by the solar system during October through June. The total heating Q_L for October through June (from part 1 of this example) is 108×10^8 Btu (114×10^8 kJ). Hence, the solar system provides 45 percent of the annual heating requirement.

For the 3 months not considered above, it is assumed that all domestic hot water heating is performed by the solar energy system. Thus,

$$Q_{LS} = 48.8 \times 10^8 \text{ Btu} + 3(.6 \times 10^8 \text{ Btu})$$

$$= 50.6 \times 10^8 \text{ Btu } (63.5 \times 10^8 \text{ kJ})$$

and

$$Q_L = 107.9 \times 10^8 \text{ Btu} + 3(.6 \times 10^8 \text{ Btu})$$

$$= 109.7 \times 10^8 \text{ Btu } (115.7 \times 10^8 \text{ kJ})$$

Hence, the annual ϱ is

$$\varrho = \frac{Q_{LS}}{Q_L} = .46$$

Thus, the 50,000 sq ft (4645 m²) of collectors will meet 46 percent of the heating and hot water load for a total energy savings of 50.6×10^8 Btu (53.4×10^8 kJ) compared with Example 2, where the same 50,000 sq ft (4645 m²) of collectors met only 26 percent of the heating and cooling load but had a total energy savings of 78.4×10^8 Btu (82.7×10^8 kJ).

Corrections for Different Collector Types

As previously described, the universal curves were developed for the reference solar collector. For collectors with different absorber plate characteristics and different numbers of covers, Tables 5 and 6 can be used to correct the results of the universal curve. These tables give values for a collector area multiplication factor which can be applied when a particular collector other than the reference collector is used. In these tables, a is the absorptivity and ε is the emissivity of the absorber plate. The transmit-

Table 5

Collector Area Multiplying Factors for Different Collector Designs for Heating and Cooling Systems

a		**0.96**	**0.94**	**0.90**
ε		**0.96**	**0.30**	**0.10**
N	1	1.55	1.09	1
	2	1.09	0.97	0.93

a = Absorptivity
ε = Emissivity
N = Number of glass covers

Table 6

Collector Area Multiplying Factors for Different Collector Designs for Domestic Hot Water Heating and Heating-Only Systems

a		**.96**	**.90**
ε		**.96**	**.10**
N	1	1.26	1
	2	.96	.93

a = Absorptivity
ε = Emissivity
N = Number of glass covers

tance of each cover was assumed to b 0.9, so that for two covers, the transmittance equals 0.81. These tables are useful because they permit application of the performance curves for the reference flat-plate collector (a single-cover collector with an absorptivity of 0.9 and emissivity of 0.10) to other flat-plate collectors. For example, in order to achieve equivalent performance for heating and cooling from a two-cover, nonselective collector, one would multiply the appropriate collector area for the reference collector by 1.09 or increase the collector area by 9 percent.

4 DETERMINING THE OPTIMAL COLLECTOR AREA

This chapter describes a method for defining the optimal collector area which is based on a life-cycle cost comparison of the solar energy system and a conventional energy system. The procedure is adapted from that suggested by Butz, et al.[8]

The method relies on a simple graphical comparison of the life-cycle cost difference between a solar energy system and a conventional energy system, where the solar system performance is determined from the universal curve as described in Chapter 3. The Office of the Chief of Engineers (OCE) life-cycle cost instructions[9] should be used. Since the purpose of this optimization method is to determine the economically optimum collector array, life-cycle cost differences are examined rather than total system life-cycle costs. Normal procedures and instructions for determining overall building and energy system capital and life-cycle costs of various options can be followed once the optimum system is determined.

The first step in determining the optimum collector area is to estimate the life-cycle cost of the solar energy system components.* Because the method being described is comparative, only the cost of components that are not normally part of the conventional heating and cooling system should be considered. For example, the cost of the building's air-handling system would not be considered, but the difference between the cost of a more expensive absorption chiller and a less expensive centrifugal chiller should be charged to the solar energy system.

Certain cost elements for solar energy systems vary according to the size of the solar energy system, while others are relatively fixed regardless of collector area or tank size. Collector and storage tank costs are obvious examples of costs which are dependent on collector area. (The tank volume is assumed to be 16 lb of water per square foot of collector [78 kg/m^2].) Other examples include heat exchanger costs and certain pump and piping costs. Additional control system costs associated with the solar energy system are an example of cost differences which are largely independent of collector area. The cost difference associated with the purchase and installation of an absorption chiller is also relatively independent of solar collector area, since the selection of an appropriate absorption chiller is dictated by peak building cooling load for all but the smallest solar collector areas. It is important that these costs be apportioned appropriately since the method compares the life-cycle cost difference between conventional and solar energy systems as a function of the area of the solar collector array.

When determining the increased capital cost of the solar system, care must be given to specifying the type of auxiliary system to be used and to taking the appropriate credits for any reduction in capital costs for the conventional system. Also, the costs for the auxiliary energy must be compatible with the auxiliary system being used. For example, most solar systems have a complete conventional system as an auxiliary. For solar heating and cooling systems which require absorption chilling, the auxiliary can be a boiler for the absorption chiller or an auxiliary centrifugal chiller. In the first case, capital cost is low, since a credit can be taken for the centrifugal chiller because the boiler is required anyway for the heating system. The fuel costs, however, may be high, since the absorption chiller has a COP on the order of .65. In the second case, the capital costs are higher, since credit for the centrifugal chiller cannot be taken. However, since this chiller has a COP on the order of 4.2, the fuel cost may be considerably lower. Note that, in the first case, heating fuel is the auxiliary fuel while in the second case, electrical power is.

Once the cost data have been determined, the second step in the comparison procedure is to establish a life-cycle fuel cost for conventional energy

[8] L. W. Butz, et al., *Use of Solar Energy for Residential Heating and Cooling*, Masters Thesis in Mechanical Engineering (University of Wisconsin, 1973).

[9] *OCE Life Cycle Costing Instructions* (Department of the Army, May 1971).

*This report does not include cost data, since solar component costs are changing rapidly. Manufacturers are the best source of data.

systems. For a conventional system, annual fuel costs can be estimated as follows:

1. Determine the annual heating and/or cooling energy requirement for conventional equipment as described in Chapter 2.

2. Convert the cooling energy load to kilowatt hours and multiply by the local electrical rate to obtain the cost of cooling energy (note that the COP of the conventional electrical chilling device must be considered in making this conversion).

3. Divide the input heating energy and/or domestic hot water heating energy required by the heating value of the fuel used and multiply by the unit fuel price to determine the cost of heating (note again that in determining the heat energy required, the efficiency of the boiler or furnace must be considered).

4. Add results of steps 2 and 3 to obtain the total annual fuel cost for the conventional system.

5. Convert the annual fuel cost to life-cycle cost. This value provides the baseline for comparison of solar energy systems.

The third step is to calculate the amount of auxiliary fuel or electrical energy required annually by the solar system being considered for various collector array sizes based on the methods described in Chapter 3. Procedures for determining life-cycle costs for various solar energy systems are as follows:

1. Determine the total annual auxiliary energy requirement for a given collector area and system type, Q_{LA}, using the method described in Chapter 3.

2. Determine the annual energy cost for auxiliary heat similarly to conventional systems. For heating and cooling systems, assume that the auxiliary energy requirement is for cooling only. Note in particular that if centrifugal or other electrical chilling devices are to be used to augment the solar cooling system, the appropriate COPs for absorption and electrical refrigeration equipment must be used in determining the auxiliary energy that will be required to meet the cooling demand not met by the solar system. If a boiler is used to drive the absorption chiller, the boiler efficiency must be used.

3. Convert the annual auxiliary fuel cost to life-cycle cost.

The total life-cycle cost difference between conventional and solar heating and cooling systems can now be determined for various collector areas. For a given collector area, this difference is simply the life-cycle capital cost difference of the solar energy system plus the life-cycle fuel cost for the auxiliary system minus the life-cycle fuel cost of the conventional system. Figure 4 is the hypothetical plot of this cost difference for varying collector areas.

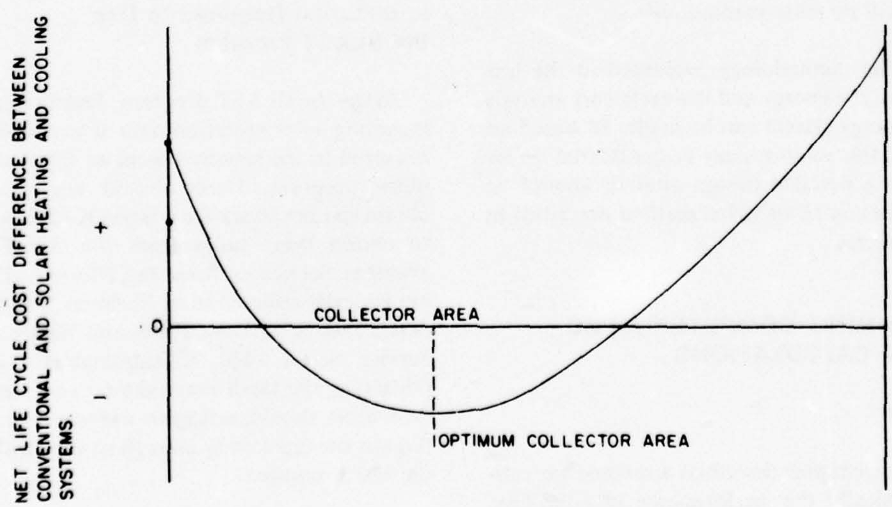

Figure 4. Net life-cycle cost difference vs. collector area.

Appendix B provides a detailed example which further illustrates application of this technique.

The shape of the curve in Figure 4 is fairly easy to visualize. For very small collector areas, there is very little fuel savings to offset the fixed costs of the system such as the controls, added piping, and pumps, etc. As collector area increases, the increased fuel savings start to offset the fixed costs of the system, and the cost difference between solar and conventional costs decreases. As more collectors are added, a point of diminishing returns is reached; added collector area adds very little additional fuel savings. Thus, the added costs of collectors and tank volume cannot be offset by the fuel savings of those collectors, and solar system cost starts to increase with respect to conventional system costs.

When the cost difference for the solar energy system being considered has been plotted in the form of Figure 4, the optimum collector area becomes obvious; it is the area at which the net life-cycle cost difference between conventional and solar heating and cooling systems is minimized. Note that Figure 4 concisely summarizes the economics of solar systems. The points on the curve having a positive cost difference indicate that solar energy is not cost effective. Only when the curve dips below the origin can a solar energy system be economically justified. Based on present solar energy system costs, many applications may not have such a negative cost difference. In fact, if the costs of collectors and tanks are so high that the fuel savings cannot offset even those costs which vary with collector area, the curve in Figure 4 will increase continuously.

Based on the methodology presented in the last three chapters, the energy and life-cycle cost analysis of the solar energy system can be made. If, based on this analysis, the solar system is considered to be feasible, then a detailed design analysis should be made using the computer-aided method described in the next chapter.

5 PERFORMING COMPUTER-AIDED DESIGN CALCULATIONS

Introduction

The previous chapter described a method for estimating graphically the performance of candidate solar domestic hot water, building heating, or building heating and cooling systems. This method is sufficiently accurate for the preliminary energy and life-cycle cost analysis of solar energy systems. For most projects, however, selecting the optimum collector area and type and insuring the selection of the appropriate collector tilt angle and storage tank volume may require a more detailed design analysis. The methods described in this chapter are based on the application of the BLAST program developed at CERL. This program permits hourly simulation of building loads, and of air-handling systems meeting the various loads in the building, and simulation of central energy plant equipment supplying the air-handlers, including solar energy systems. Designers who wish to use this program should obtain the users and reference manuals which describe the preparation of the input required for using the program and the algorithms employed in performing the simulation.

The optimum design using the simulation model is again determined by performing the economic analysis as described in Chapter 4. The simulation tools, however, allow better determination of system performance and, thus, a more accurate measure of ϱ, the fraction of the load met by the solar system for a given collector array. Also, other variables such as collector tilt angle, storage tank volume, and type of collector can be varied to maximize ϱ. In addition, the BLAST program allows for the analysis to be performed using more accurate values of the building energy requirements, Q_L, since assumptions concerning average efficiency and COP do not have to be made.

Information Required to Use the BLAST Program

To use the BLAST program, hourly weather data, including solar radiation data if available, must be acquired in the required form as input to the computer program. Users should contact CERL to obtain the necessary data tapes (CERL will arrange to obtain these tapes from the Air Force's Air Weather Service or from the NOAA). These tapes are typically referred to as National Weather Service Series 280, Solar Data Tapes and National Weather Service Series 1440, Climatological Data Tapes. Obtaining the tapes may take up to 6 weeks; therefore, users should anticipate use of the program and request the tapes early enough so they will be available when required.

The BLAST program requires a description of the building as input. The users manual describes the

exact form of this input. The program uses such information as the type of wall construction, window orientation, schedule for occupancy, and electrical demands in determining the hourly building zone loads and hourly total load of the building. If measured data are available, they can frequently be used to check the building loads to insure that parameters were properly defined and reflect the actual building, since some parameters, such as infiltration and occupancy, are hard to determine.

The air-handling systems used in the building must also be described. In this case, such information as the zone air flow rate, type of coil, type of air-handling system, and type of control system used are specified by the user. The output from the air distribution system simulations is the hourly energy demand on the boilers and chillers serving the air handlers in the building. These hourly demands form the input to the central plant simulation program which determines the expected performance of conventional and solar energy system components. In performing the central energy plant simulation, the user can specify the performance of the solar collector, the collector area, and the storage tank volume being used in the system. The type of performance data required for solar collectors is identical to that described in National Bureau of Standards publication NBSIR-74-635.[10] The slope and intercept of solar collector efficiency curves are the input parameters required.

Note that in the analysis of the solar energy systems, the BLAST program should first be used to minimize the energy required by each zone by studying such effects as added insulation and changes in window area and orientation. This should be followed by a comparison of various air-handling systems and control schemes to minimize the energy demanded by the boilers and chillers, assuming these design changes can be made to the building. Once this analysis has been performed, various collector systems must be simulated to optimize the performance of the candidate systems and to establish the optimum system configuration.

Once the load profiles for the boilers and chillers have been determined, the optimization of the solar energy system can be initiated.

[10] J. S. Hill and T. Kusuda, *Methods of Testing for Rating Solar Collectors Based on Thermal Performance*, NBSIR-74-635 (National Bureau of Standards, 1974).

Setting Up the Solar Energy Detailed Design Study

The computer-aided design should not be initiated until the graphical life-cycle cost analysis described in the previous chapter has been completed, since the results of that study provide the starting point for the computer-aided study. If the life-cycle cost study has been completed, but the loads determined from the BLAST program are considerably different than those used in the life-cycle cost analysis, the analysis should be repeated. The graphical method serves to bracket the area of consideration.

In order to optimize the design, certain variables not previously considered should be varied to establish their optimum value, as discussed in the following section. The starting point should be the solar system obtained from the universal curve analysis which set the optimum collector area. The collector array should be set with an azimuth angle of 180 degrees (i.e., facing due south) and tilted at the optimum angle as described in Chapter 2. The tank volume should be set at 16 lb/sq ft of collector (78 kg/m^2).

Methodology for Optimizing the Solar System Design

The optimization proceeds in the following steps:

1. First, several simulations are run using the BLAST solar simulation package with different tilt and azimuth angles for the collector array. Figure 5 illustrates how the output from such a parametric study can be plotted to establish the optimum tilt for a given azimuth. A similar plot of system performance versus azimuth angle will indicate the optimum azimuth.

2. The next step is to vary the collector area while keeping the collector-area-to-tank-volume ratio constant (start with 16 lb/sq ft of collector [78 kg/m^2]) and repeat the economic analysis described in Chapter 4, obtaining a curve similar to Figure 4. The lowest dip in the curve is the optimum collector area for this collector-area-to-tank-volume ratio. (Note that this is a repeat of the universal curve analysis using the more precise computer analysis tools.)

3. The third step is to repeat the previous step for different collector-area-to-storage-tank-volume ratios. All life-cycle cost curves can be plotted on the same graph. Sufficient ratios should be examined to determine the curve with the lowest dip. If no other

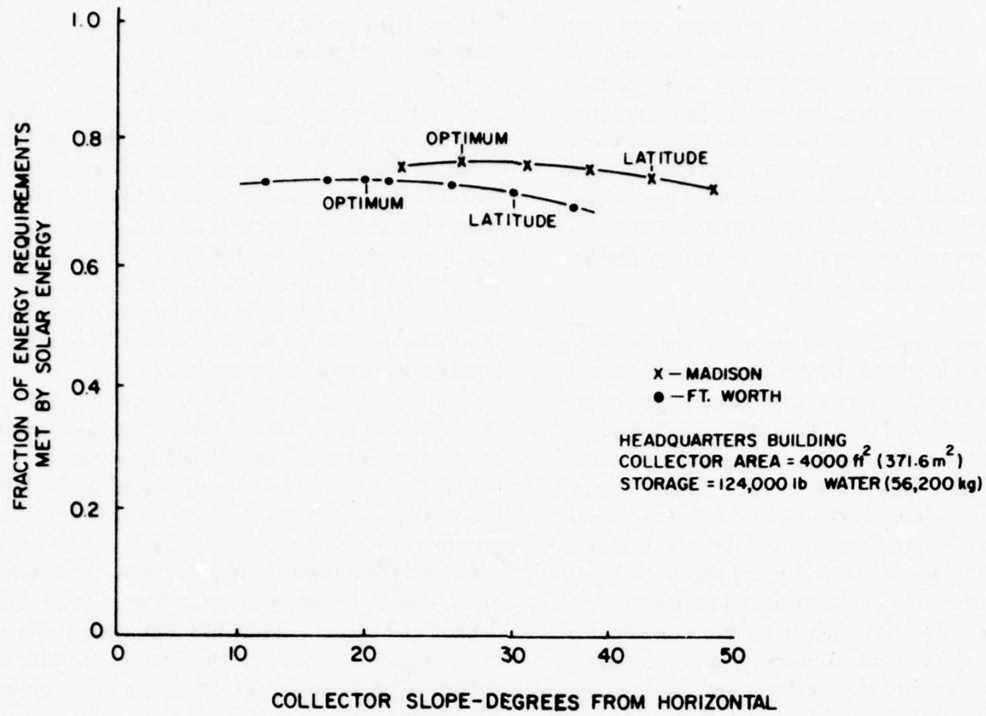

Figure 5. System performance vs. collector slope.

information is available, 8 and 32 lb/sq ft (39 and 156 kg/m^2) are good second and third tries. Subsequent tries are based on the results of these simulations. The curve with the lowest dip gives the optimum tank-volume-to-collector-area ratio, while the point at which the dip occurs establishes the optimum collector area. Although the better the tank insulation, the larger the optimum tank volume will be, high tank insulation (especially for buried tanks) is unfortunately difficult to achieve in practice. Therefore, tank-volume-to-collector-area ratios which greatly exceed 16 lb/sq ft (78 kg/m^2) should be examined critically to insure the specified tank insulation values can be obtained.

4. The final step is to vary the type of collector to see what effects this has on system life-cycle costs. The optimum tank-volume-to-collector-area ratio found in Step 3 should not be significantly affected by the type of collector. The life-cycle cost difference versus collector area curves should be constructed as before by simulating several different areas for each collector type being considered.

Note that the only differences between the graphical and computer-aided methods for determining system performance and optimal collector configuration are that the simulation model provides a more accurate estimate of the performance of a candidate solar energy system and permits a more refined study of the secondary effects of collector tilt, azimuth angle, and storage tank capacity.

6 PRACTICAL CONSIDERATIONS

Discussions in the previous chapters focused on estimating performance of solar collector systems. This chapter deals with some practical considerations involved in the final design, installation, and operation of solar energy systems and is based on experience gained in the construction and operation of the CERL solar facility.

Controls

The controls of solar energy systems typically do not require new control technology. However, special care must be exercised in the control of the collector array. The most convenient way to control the collector pump which determines when the collector is or is not collecting energy is by sensing the temperature difference between the collector plate surface and the storage tank. When a positive difference exists

(i.e., the collector is hotter than the storage tank), useful energy can be collected and the collector system should be energized. However, any time the collector plate is cooler than the storage tank, the system will dissipate or waste heat through the collector array if it is energized. Thus, care must be taken to insure that when a negative difference exists between the temperature of the collector absorber plate and the temperature in the storage tank, the system is turned off. At the same time, minimizing the difference between those two temperatures when the system is to be turned on is desirable. For example, it might be appropriate to establish a 10°F (6°C) difference between the collector plate and the storage tank for energizing the system and a 5°F (3°C) difference for de-energizing it.

It is also important that the control system maintain its linearity over the entire region of control. For example, turning the collector loop on may be required when the collector is 185°F (85°C) and the tank is 180°F (82°C) during the summer. During the winter, the temperature may be 125°F (52°C) on the collector surface and 120°F (49°C) in the tank; thus, the measurement of temperature at the plate and in the tank and the subsequent sensing of the temperature difference between the two require linear control over a broad temperature range.

Piping of the Auxiliary Energy Supply

For practical solar energy systems, some auxiliary energy supply will be required. Since there are many possible configurations, individual cases must be examined to determine where auxiliary energy will be derived. However, any auxiliary supply boiler or other device should be piped parallel with the solar energy solar tank. Figure 6 illustrates the correct and incorrect methods for piping an auxiliary energy supply. If the auxiliary supply is piped in series with the tank, under conditions of low tank temperature the auxiliary supply will not only be required to meet the heat energy demands of the building but will also begin to add energy to the tank. This is particularly undesirable because it will require an unnecessarily large auxiliary heater capable of meeting the instantaneous demand while at the same time supplying an added demand by delivering energy to the storage tank. It is also undesirable because the stored energy should be derived only from the solar energy system; application of auxiliary heat to the stored energy raises the tank temperature, reducing collector efficiency and increasing tank heat losses.

Use of Two-Position Valves

Another consideration in the practical application of solar energy is that free convection be prevented from dissipating solar heat through the collector bank when the solar energy system is not in operation. The application of two-position valves which close when the collector system is de-energized is recommended to prevent this.

Venting the Collector Loop

Particular attention must be given to the possibility of air accumulating in the collector array. A frequent problem encountered in the past has been accumulation of pockets of air at the top of the collector bank. These air pockets prevent the fluid from passing over the collector absorber plate, thus reducing the area over which solar energy is collected. Such "vapor locking" can be prevented by generous use of automatic or manual vents in the collector system and by insuring that sharp bends or other piping arrangements which can lead to air being trapped are avoided. Air separators in the collector loop are also recommended.

Piping of Hot Fluids

Additional caution should be exercised in positioning pumps in the system, particularly where the storage tank is to be maintained at or near atmospheric pressure. A potential cause of system failure is the cavitation of pumps used to pump hot fluids. Piping considerations should include assurances that both the collector loop and storage tank are positioned such that net positive suction exists at the pump at all times to prevent flashing when the pumps are energized. Self-priming pumps should be used whenever appropriate.

Storage Tank Insulation

Practical experience indicates that the heat loss from insulated tanks is frequently higher than predicted. For buried tanks in particular, special care must be taken to insure that an impenetrable vapor barrier surrounds the insulation on the tank. Conservative buried tank volumes should be considered to minimize the heat loss. This consideration is less important for tanks located inside the building. However, such tanks occupy valuable floor space whose worth should be considered in analyzing the cost of the tank. Also, in applications where cooling is considered, the location of tanks inside the build-

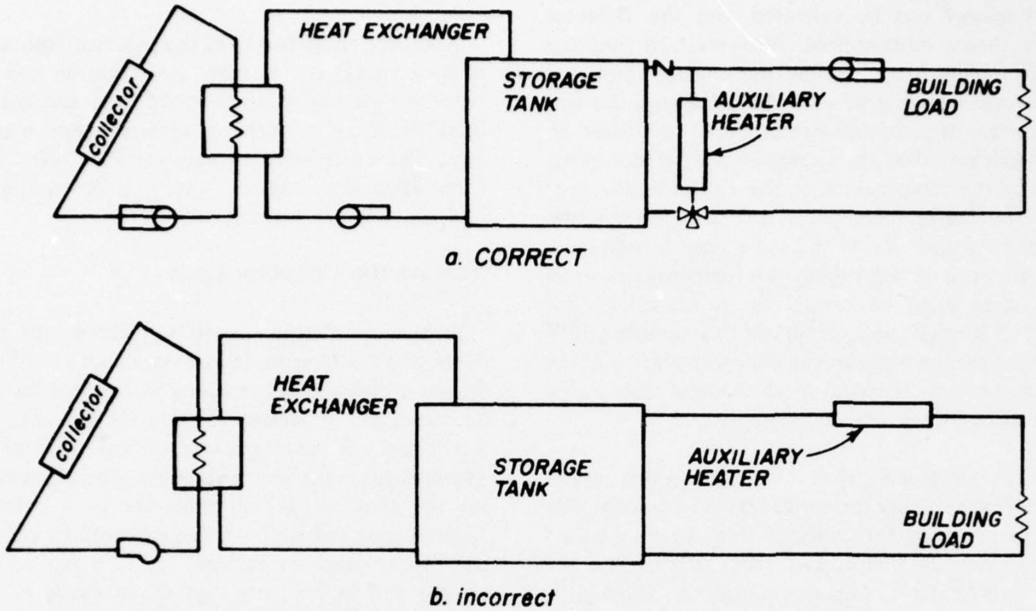

Figure 6. Piping the auxiliary energy supply.

ing must be considered so that they do not contribute to the overall cooling load in the summer.

7 CONCLUSIONS

The following conclusions can be drawn concerning the methods presented in this report:

1. The graphical method of evaluating solar energy systems is based on established technology and calculation methods, and provides sufficient accuracy for use in feasibility studies.

2. The life-cycle cost analysis method includes all cost factors which must be considered in evaluating solar energy systems, and interfaces directly with the OCE life-cycle cost analysis instructions.

3. The computer simulation method is based on established calculation methods and can be used in preparing design instructions and evaluating final designs.

4. The input data required for both the graphical and computer simulation methods can be readily obtained by District personnel.

8 FUTURE PLANS

Both the graphical and computer procedures for making a solar system energy and life-cycle cost analysis will be field tested in fiscal year 1977 (FY 77) at a Corps of Engineers District office which is currently performing a solar system study. The field test will determine if the procedures are clear and user-oriented and whether the input data are available. Based on the results of the field test, the procedures will be revised to make them more understandable and easier to use.

The graphical and computer simulation performance evaluation tools will be validated using actual data from solar demonstrations at CERL and Army installations during FY 77 and FY 78.

During FY 78 the revised procedures will be implemented by Corps Districts, and training sessions in their use will be given.

APPENDIX A:

SOLAR RADIATION DATA*

*From *Climatic Atlas of the United States* (National Oceanic and Atmospheric Administration, 1968).

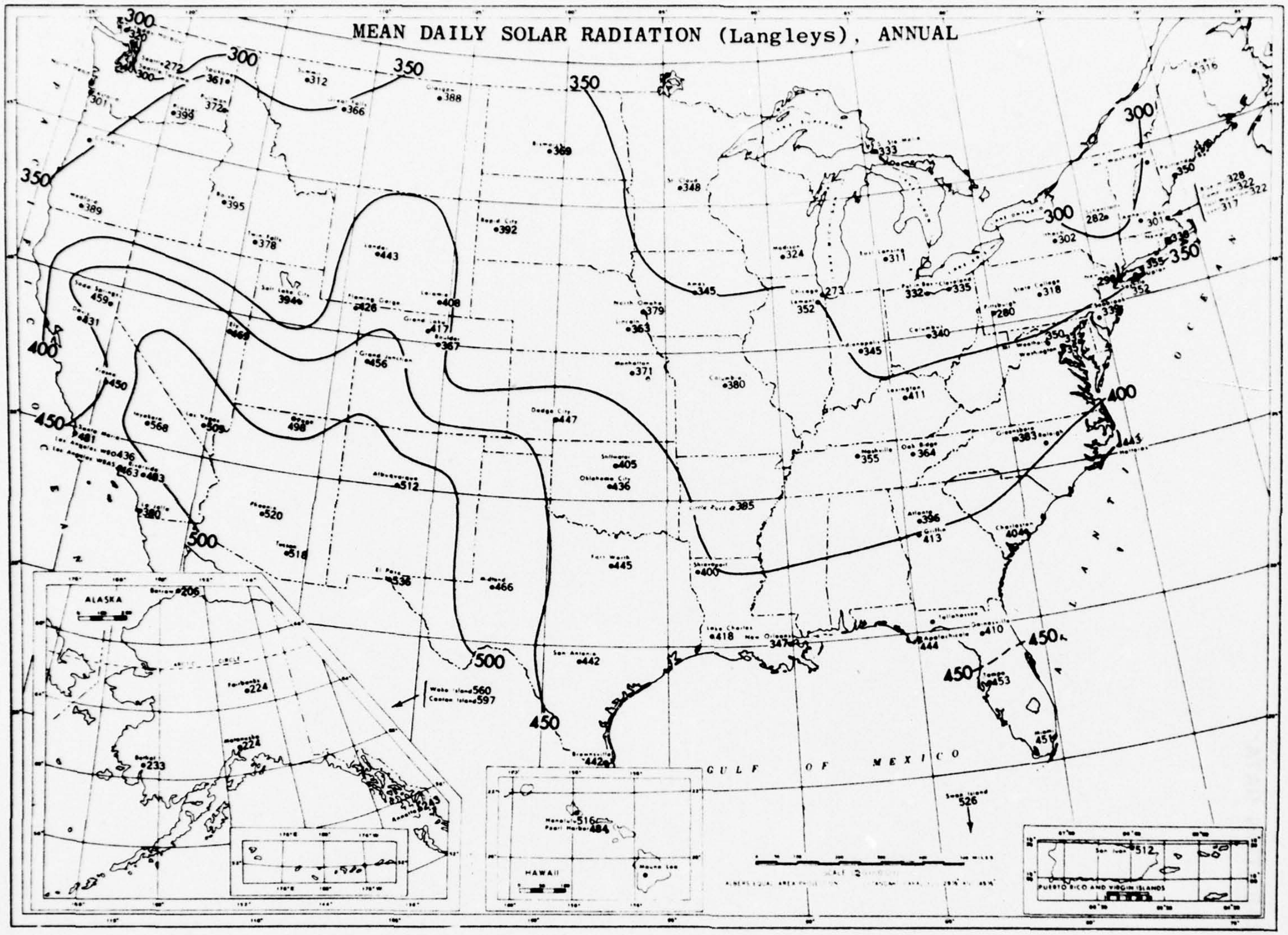

Figure A1. Annual mean daily solar radiation.
Conversion factor: 1 langley = 3.69 Btu/sq ft or 41.84 kJ/m^2.

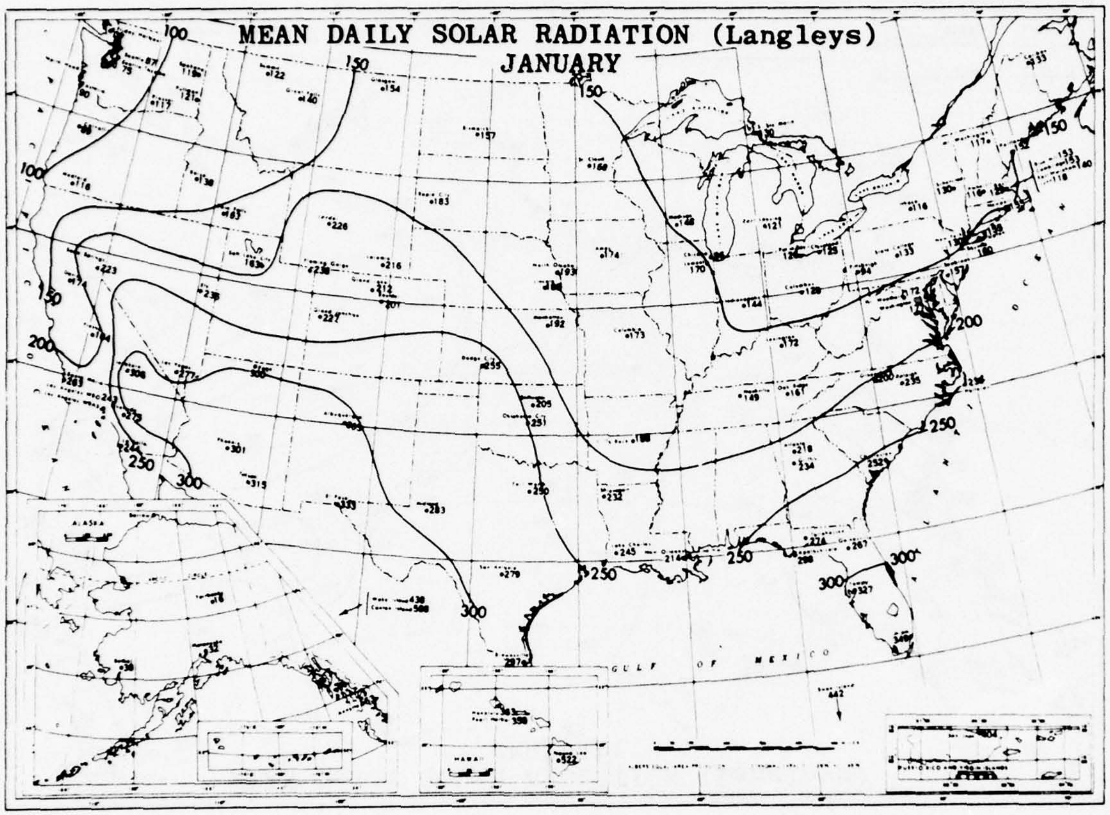

Figure A2. Mean daily solar radiation for January.
Conversion factor: 1 langley = 3.69 Btu/sq ft or 41.84 kJ/m².

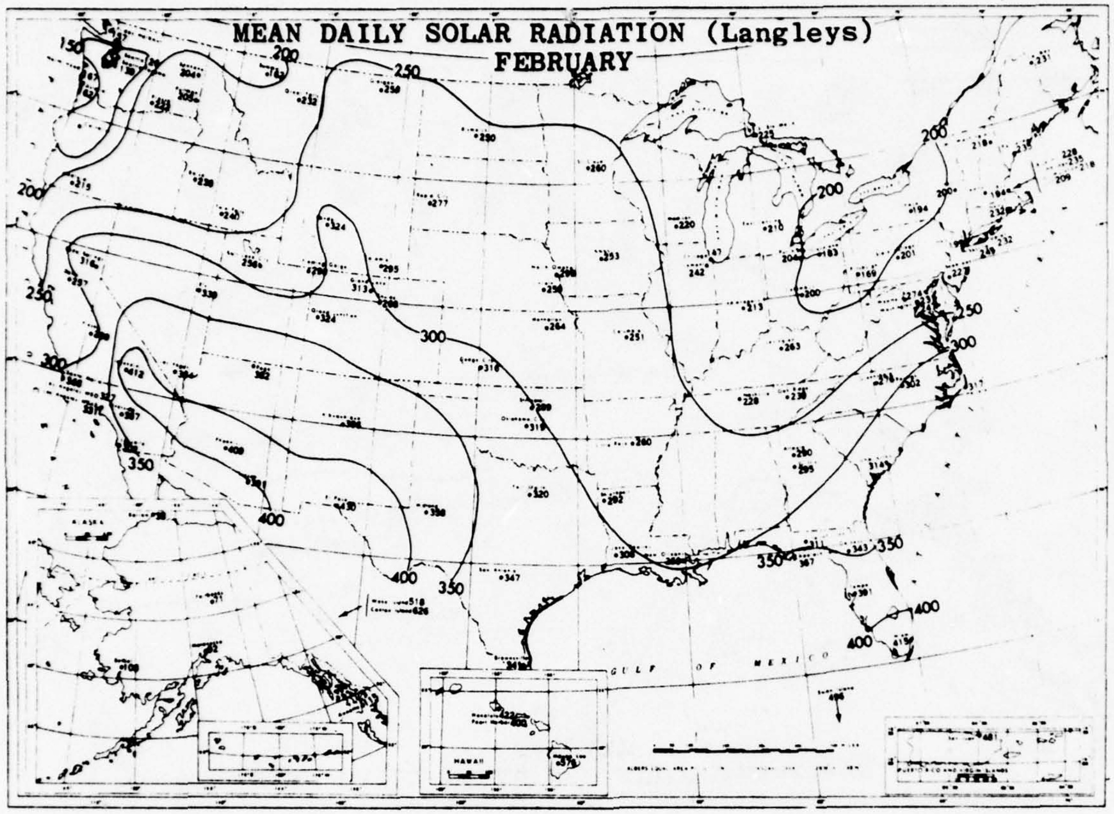

Figure A3. Mean daily solar radiation for February.
Conversion factor: 1 langley = 3.69 Btu/sq ft or 41.84 kJ/m².

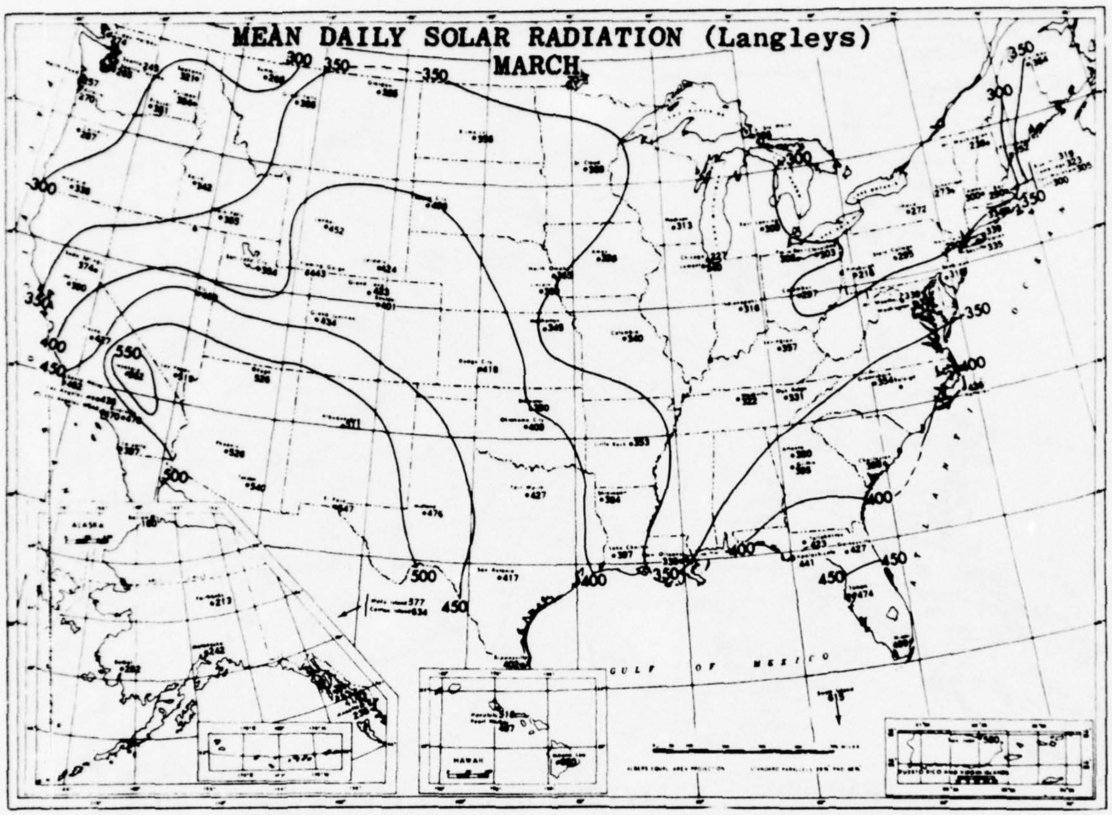

Figure A4. Mean daily solar radiation for March.
Conversion factor: 1 langley = 3.69 Btu/sq ft or 41.84 kJ/m².

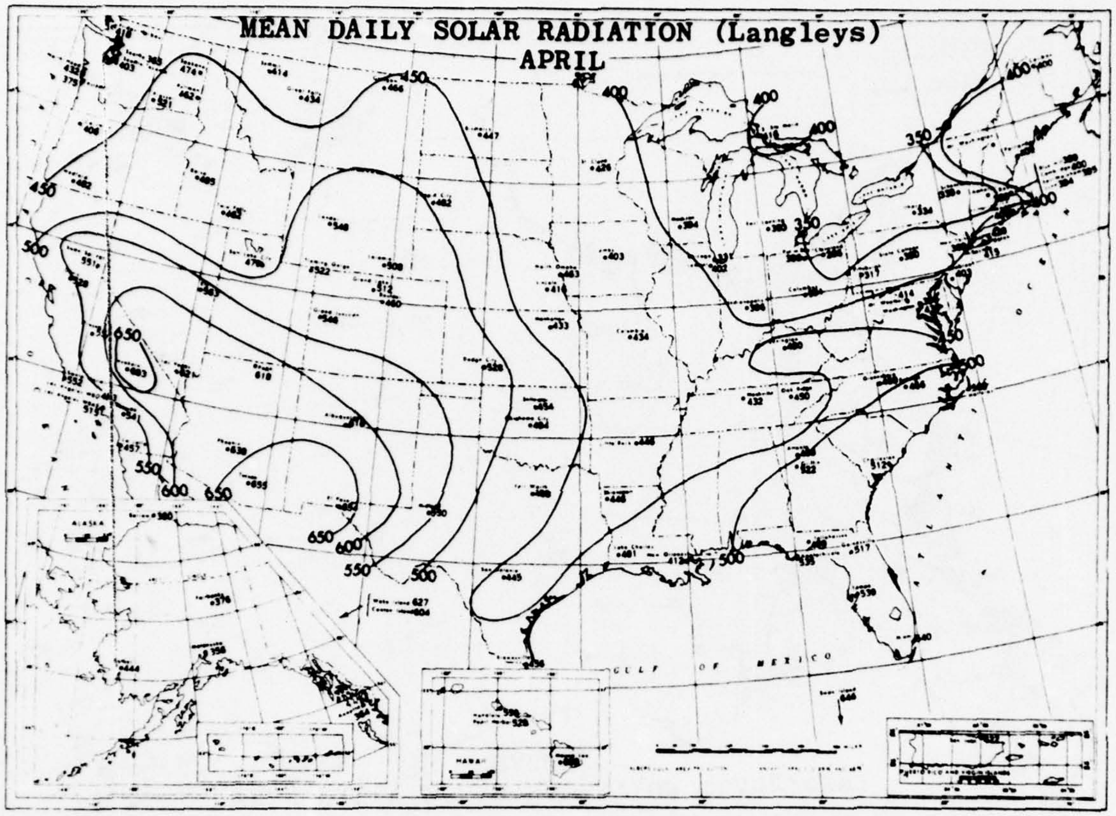

Figure A5. Mean daily solar radiation for April.
Conversion factor: 1 langley = 3.69 Btu/sq ft or 41.84 kJ/m².

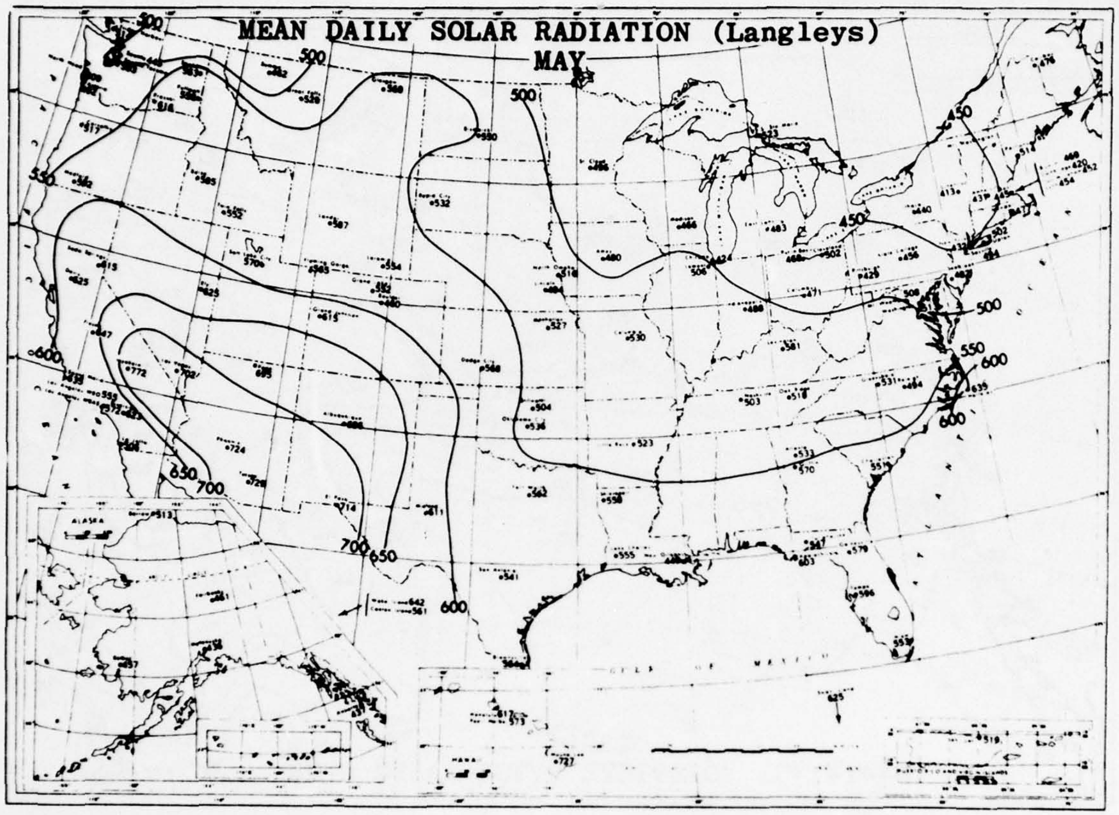

Figure A6. Mean daily solar radiation for May.
Conversion factor: 1 langley = 3.69 Btu/sq ft or 41.84 kJ/m².

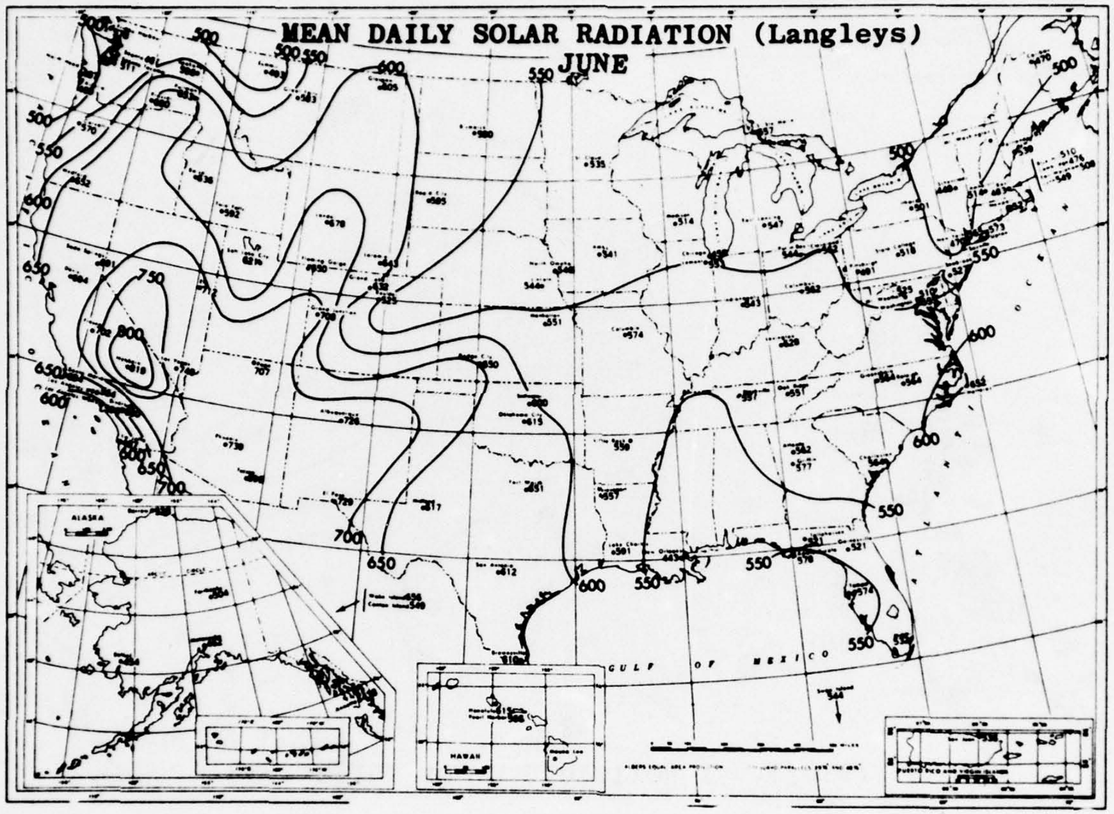

Figure A7. Mean daily solar radiation for June.
Conversion factor: 1 langley = 3.69 Btu/sq ft or 41.84 kJ/m².

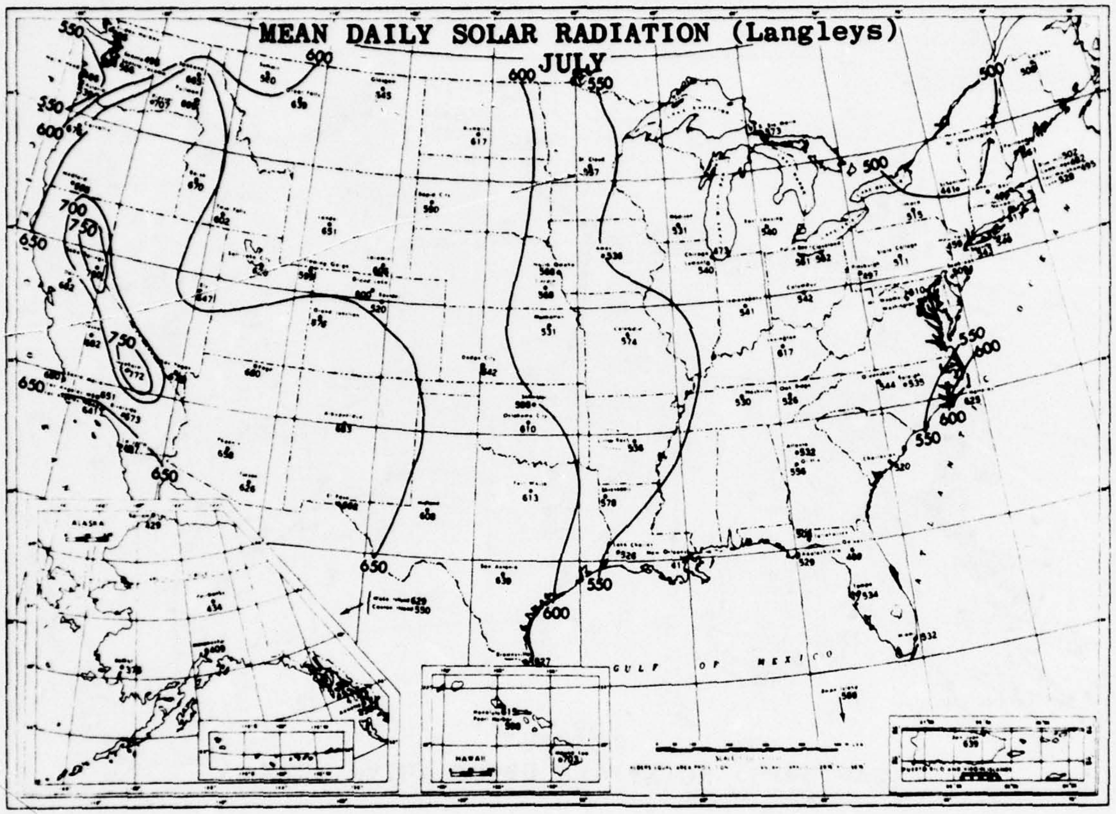

Figure A8. Mean daily solar radiation for July.
Conversion factor: 1 langley = 3.69 Btu/sq ft or 41.84 kJ/m².

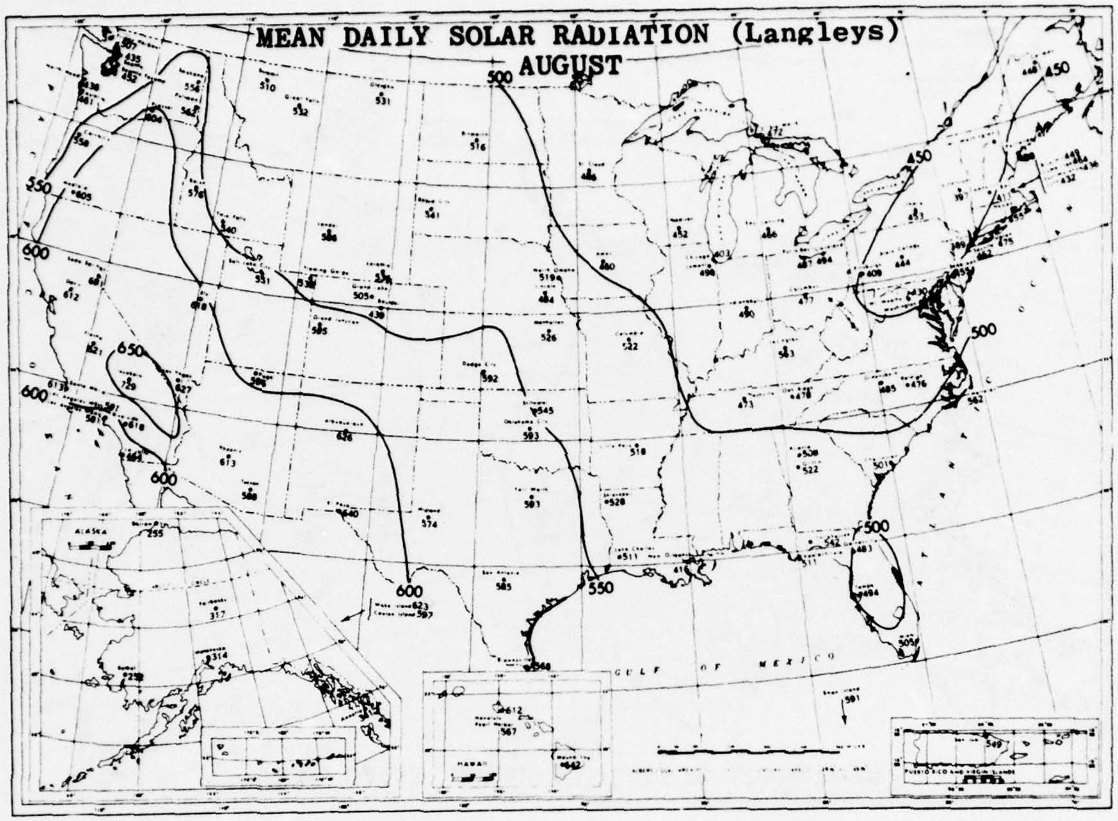

Figure A9. Mean daily solar radiation for August.
Conversion factor: 1 langley = 3.69 Btu/sq ft or 41.84 kJ/m².

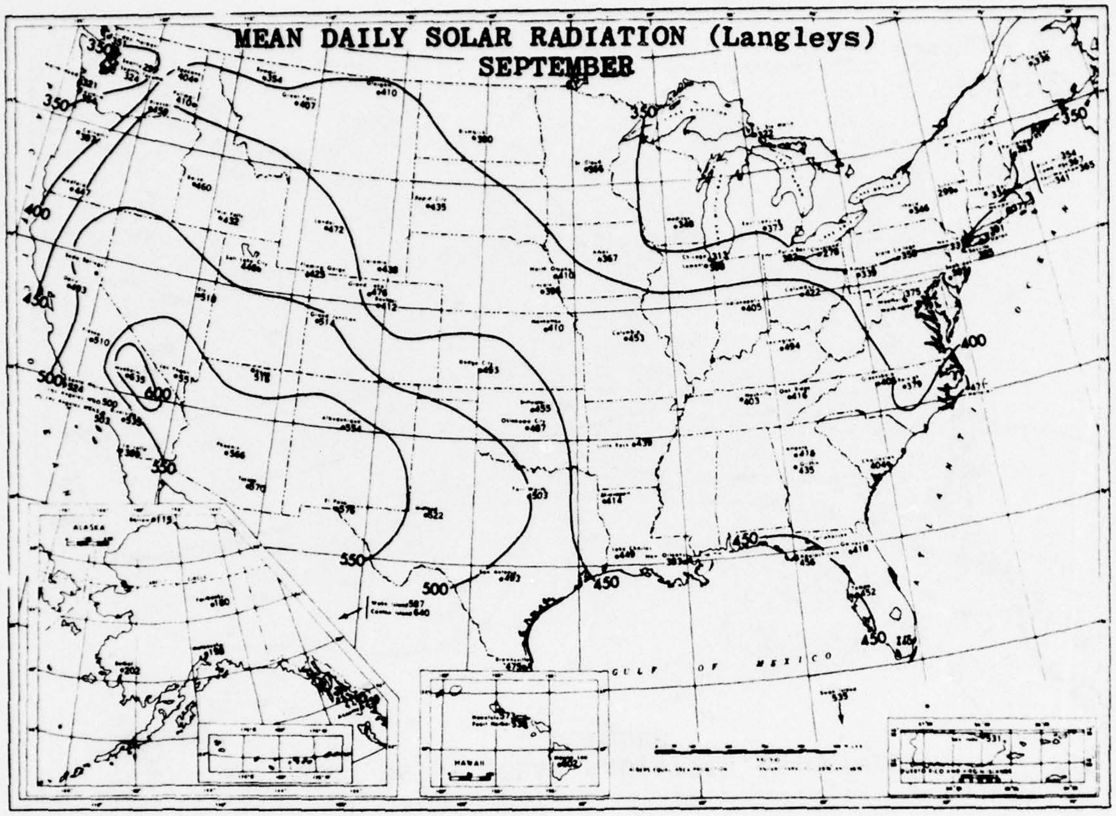

Figure A10. Mean daily solar radiation for September.
Conversion factor: 1 langley = 3.69 Btu/sq ft or 41.84 kJ/m².

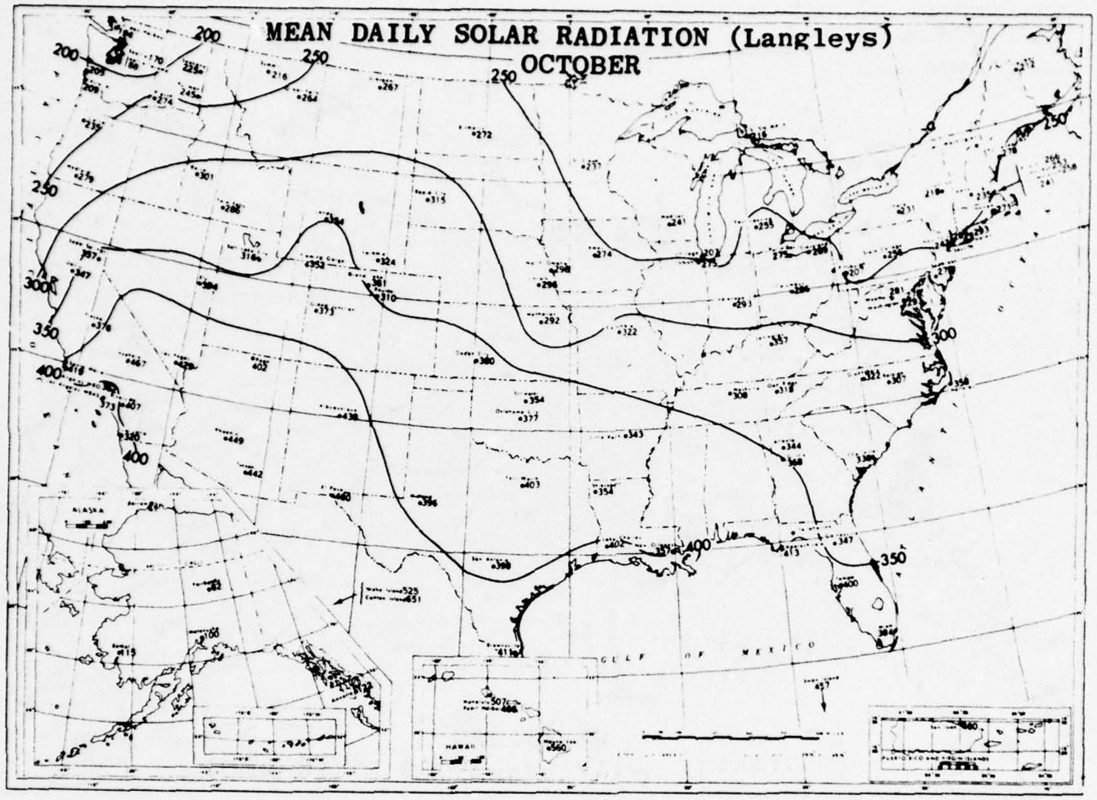

Figure A11. Mean daily solar radiation for October.
Conversion factor: 1 langley = 3.69 Btu/sq ft or 41.84 kJ/m².

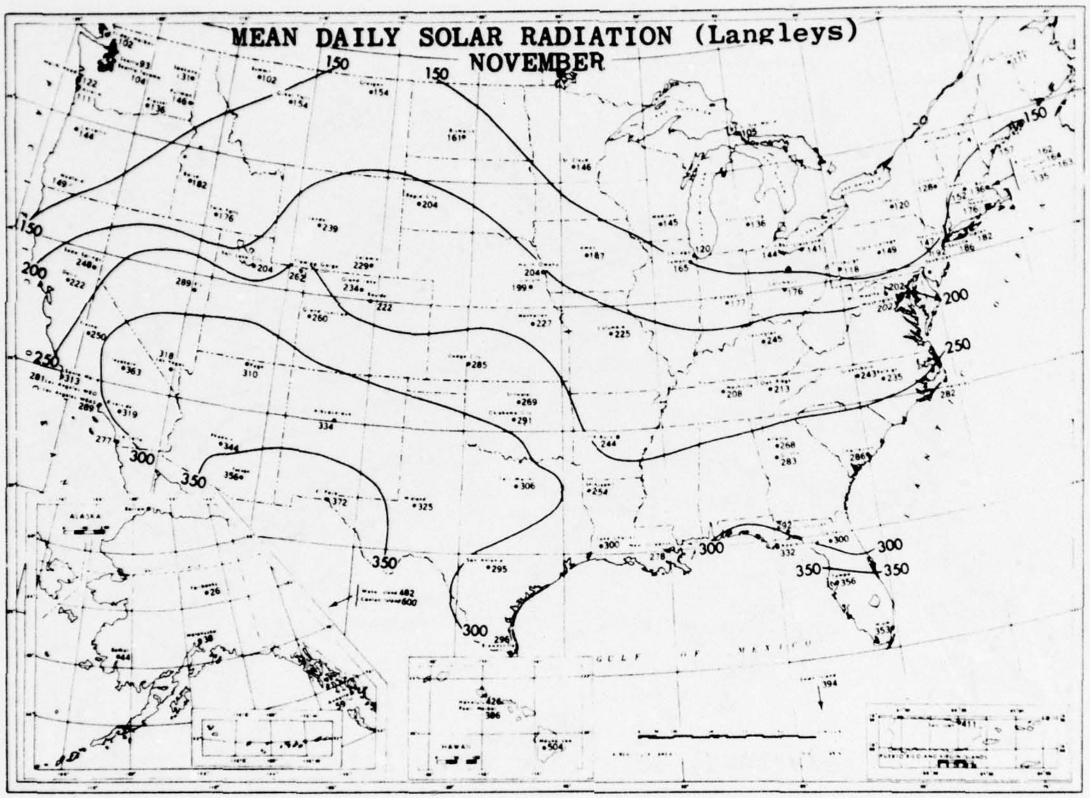

Figure A12. Mean daily solar radiation for November.
Conversion factor: 1 langley = 3.69 Btu/sq ft or 41.84 kJ/m².

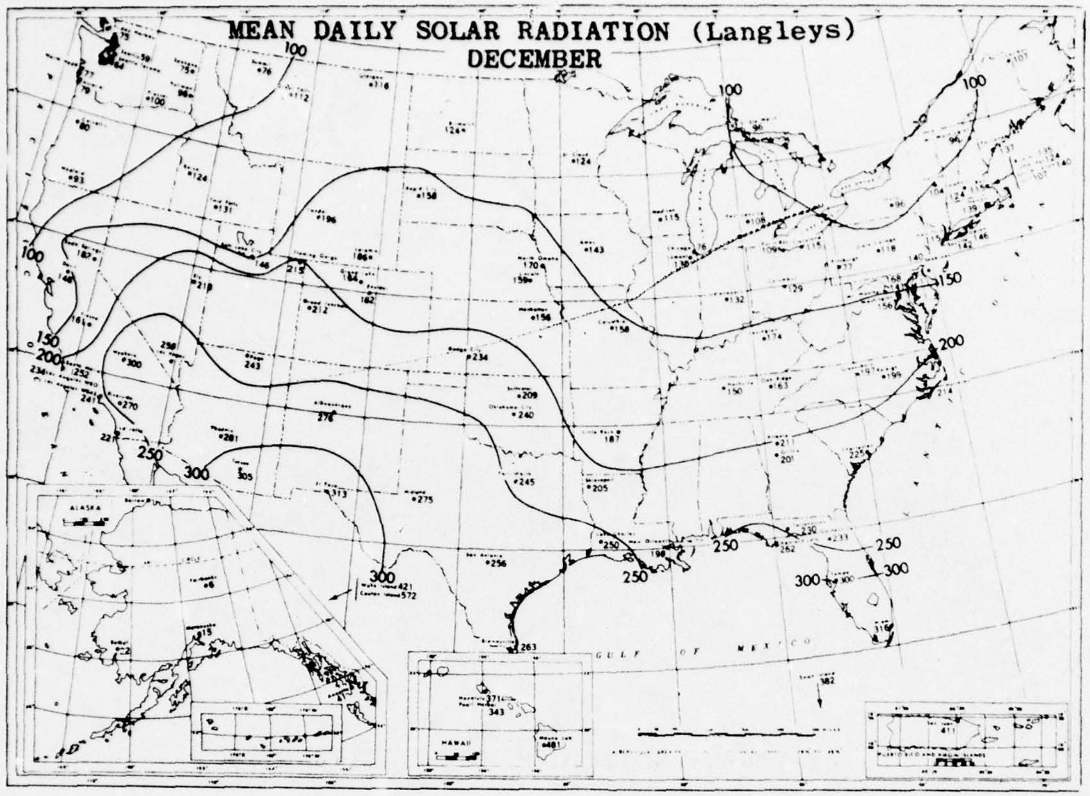

Figure A13. Mean daily solar radiation for December.
Conversion factor: 1 langley = 3.69 Btu/sq ft or 41.84 kJ/m².

APPENDIX B:

EXAMPLE OF SOLAR SYSTEM LIFE-CYCLE COST ANALYSIS

A design engineer wants to determine the collector area which is economically the most feasible for solar heating and cooling of a new administration building similar to the one used for Examples 2 and 3 in Chapter 3. For the purpose of this example, he/she is to compare the costs of a conventional building with oil heating and electric centrifugal cooling to a building heated and cooled by a solar energy system. In the solar case, auxiliary heating is supplied by an oil-fired boiler and auxiliary cooling is provided by an electric centrifugal chiller.

Input Data:

From Examples 2 and 3 the annual loads are

Building Heating Load	108×10^8 Btu/yr*
Building Cooling Load	112×10^8 Btu/yr

The cost of energy is assumed to be

Price of Electricity	\$.027/kWh
Price of Oil	\$.5/gal**†

Heating and Cooling

Step 1

Following the procedure on pp 18-20 of Chapter 4, the capital costs of the solar system components must be determined. Since in this case the absorption chiller is redundant, its entire price is considered. Table B1 summarizes estimated costs.

Since the building of Examples 2 and 3 contains a 385-ton cooling unit, the cost of an absorption chiller (\$470/ton) is $\$1.81 \times 10^5$. This is the value listed in the table.

*SI conversion factor: 1 Btu = 1.055 kJ. (To avoid confusion, SI equivalents are not given in this example; instead, an SI conversion factor is given the first time a particular unit is used.)

**SI conversion factor: 1 gal = 3.785 ℓ.

†This price is used for example purposes only; it may be somewhat higher than the actual fuel cost.

Table B1

Estimated Costs for Heating and Cooling Example

	Fixed Costs, \$	Cost/sq ft* of Collector, \$
Absorption Cooling System	1.81×10^5	
Controls	3×10^3	
Heat Exchanger		.5
Fluid		.18
Storage Tank		1.0
Plumbing		.75
Pumps		.75
Collector		5.0
Labor		1.0
	$\$1.84 \times 10^5$	$\$9.18\ A_c$

*SI conversion factor: 1 sq ft = 0.0929 m².

The cost of control sensors and valves is nearly independent of system size and is estimated at roughly \$3000.

The remainder of the items in the table are dependent on collector area (A_C). These values are meant as estimates for the purposes of the example only.

Using the OCE life-cycle costing instructions, the life-cycle initial costs can be expressed as

$$CC = Y(1.84 \times 10^5 + 9.18A_c)$$

where Y = the initial cost multiplying factor.[11] For this example, Y is taken to be 2.05, assuming an interest rate of 6.5 percent and a 25-year system life.

Step 2

Once the cost data have been determined, the second step in the comparison procedure is the establishment of a life-cycle fuel cost for conventional energy systems. As described in Chapter 4, conventional system annual fuel costs are estimated as follows:

1. Determine the annual heating and/or cooling energy requirement for conventional equipment as described in Chapter 2.

For this example the heating load is 108×10^8 Btu/yr and the cooling load is 112×10^8 Btu/yr, as was shown in Examples 2 and 3 of Chapter 3.

[11] *OCE Life Cycle Costing Instructions* (Department of the Army, May 1971).

2. Convert the cooling energy load to kilowatt hours and multiply by the local electrical rate to obtain the cost of cooling energy (note that the coefficient of performance of the conventional electrical chilling device must be considered in making this conversion).

For a cooling load of 112×10^8 Btu/yr and a chiller COP of 4, the cost of cooling energy (at \$.027/kWh) is:

$$(112 \times 10^8 \text{ Btu/yr})\ (1/4) \left(\frac{\text{kWh}}{3412 \text{ Btu}}\right) \left(\frac{\$.027}{\text{kWh}}\right)$$

$$= \$2.2 \times 10^4/\text{yr}$$

3. Divide the input heating energy and/or domestic hot water heating required by the heating value of the fuel used and multiply by the unit fuel price to determine the cost of heating (note again that in determining the heat energy required, the efficiency of the boiler or furnace must be considered).

For a boiler which is 75 percent efficient, using a heating value of 150,000 Btu/gal for oil, the cost of heating (at \$.5/gal for oil) is

$$(108 \text{ Btu/yr}) \left(\frac{1}{.75}\right) \left(\frac{\$.5}{\text{gal}}\right) \left(\frac{1 \text{ gal}}{1.5 \times 10^5 \text{ Btu}}\right)$$

$$= \$4.8 \times 10^4/\text{yr}$$

4. Add results of steps 2 and 3 to obtain the total annual fuel cost, F_c, for the conventional system:

$$F_c = 2.2 \times 10^4 + 4.8 \times 10^4 = \$7.0 \times 10^4/\text{yr}$$

5. Convert the annual fuel cost to life-cycle operating cost. This value provides the baseline for comparison of solar energy systems.

The life-cycle operating cost for fuel for the conventional system (LO_c) is given by

$$LO_c = M\ F_c$$

where M = a multiplier which gives life-cycle fuel costs. For oil and a 25-year facility life, M = 42.4. Hence,

$$LO_c = (42.4)\ (\$7.0 \times 10^4)$$

$$LO_c = \$2.97 \times 10^6$$

Step 3

The third step is to calculate the amount of auxiliary fuel or electrical energy required annually by the solar system being considered for various collector array sizes based on the methods described in Chapter 3. Procedures for determining life-cycle costs for various solar energy systems are as follows:

1. Determine the total annual auxiliary energy requirement for a given system, Q_{LA}, by the method prescribed in Chapter 3. Following Example 2 of Chapter 3, Q_L is 280×10^8 Btu/yr and Q_c is 5.6×10^5 Btu/sq ft/yr. For a collector area, A_c, of 10^5 sq ft (a guess), Eq 1 may be used to find P_s

$$P_s = 2.0$$

For this P_s, the universal curve for heating and cooling (Figure 2) gives a ϱ of .49. Hence,

$$Q_{LA} = (1 - \varrho)\ Q_L = (1 - .49) Q_L$$

$$Q_{LA} = 143 \times 10^8 \text{ Btu/yr}$$

2. Determine the annual energy cost, F_s, for auxiliary fuel. (All auxiliary energy is assumed to be used for cooling.) Since a centrifugal chiller (COP of 4) supplies the cooling backups, the auxiliary fuel requirement may be determined as follows:

$$F_s = \$1.84 \times 10^4/\text{yr}$$

The factor of .65 comes from the fact that Q_L (280×10^8) was computed on the basis of absorption chiller cooling. Now that the backup system is assumed to be conventional, this factor is regained.

3. Convert the annual fuel cost to life-cycle operating cost LO_s. Once again

$$LO_s = MF_s = \$0.78 \times 10^6$$

Here the value of M is the same as for the conventional system.

Step 4

The total life-cycle cost difference (LCC) between the conventional and solar heating and cooling systems is given by

$$LCC = CC + LO_s - LO_c$$

The solar energy system represents a savings over the conventional system *only if LCC is negative.*

From Step 1, for an A_c of 1×10^5 sq ft

$$CC = 2.05\,[\$1.84 \times 10^5 + \$9.18(1 \times 10^5)]$$

$$CC = \$2.26 \times 10^6$$

Using LO_s and LO_c from Steps 2 and 3, LCC can now be computed.

$$LCC = \$2.76 \times 10^6 + .78 \times 10^6 - 2.97 \times 10^6$$

$$LCC = .07 \times 10^6$$

for a collector area of 100,000 sq ft.

A life-cycle cost difference of this magnitude is negligible when compared to the capital or fuel life-cycle costs. Hence, to within the accuracy of the method, a solar energy system of 100,000 sq ft is (for this case) equivalent to a conventional system. Other collector areas may yield greater (or smaller) differences.

If the previous calculation is repeated for an A_c of 1.5×10^5 sq ft, it is found that

$$P_s = 3$$

The universal curve gives a ϱ of .67 for this P_s; thus,

$$Q_{LA} = 92 \times 10^8 \text{ Btu/yr}$$

In the same way

$$F_s = \$1.18 \times 10^4$$

This implies

$$LO_s = \$.5 \times 10^6$$

for an A_c of 1.5×10^5 sq ft

$$CC = \$2.05[1.84 \times 10^5 + 9.18\,(1.5 \times 10^5)] = \$3.2 \times 10^6$$

Using the same LO_c as before

$$LCC = 3.2 \times 10^6 + .50 \times 10^6 - 2.97 \times 10^6$$

$$LCC = \$.73 \times 10^6$$

for a collector area of 150,000 sq ft. The larger collector area has resulted in a higher life-cycle cost.

If a collector area of 75,000 sq ft is considered, LCC is computed to be $-\$2.3 \times 10^5$. Since a cost-effective area has been found, a more exact analysis of the problem is indicated. Hence, the computer *simulation program should probably be consulted.*

Heating Only

Experience indicates that a high percentage of the auxiliary fuel requirement is normally used for cooling. This seems to suggest that a heating-only system might (from an economic standpoint) be more feasible. An example of a heating-only application follows.

Step 1

Determine capital costs. Table B2 summarizes estimated costs. For this case, the absorption chiller cost is saved, and the life-cycle capital (initial) cost, CC, is given by

$$CC = Y\,(3 \times 10^3 + 9.81\,A_c)$$

Table B2

Estimated Costs for Heating-Only Example

	Fixed Cost, \$	Cost/sq ft of Collector, \$
Controls	3×10^3	
Heat Exchanger		.5
Fluid		.18
Tank		1.0
Plumbing		.75
Pumps		.75
Collector		5.0
Labor		1.0
	3×10^3	$\$9.18A_c$

Step 2

The computation of conventional fuel costs is based on the heating load alone. For a building heating load of 108×10^8 Btu/yr, with a .75 boiler efficiency,

$$F_c = (108 \times 10^8 \text{ Btu/yr})\,(1/.75)\,(\$.5/\text{gal})$$

$$(1 \text{ gal}/1.5 \times 10^5 \text{ Btu})$$

$$F_c = \$4.8 \times 10^4/\text{yr}$$

Hence

$$LO_c = \$2.035 \times 10^6$$

Table B3

Summary of Procedure Used to Determine Q_{LS}

Month	Q_L, Btu/mo	Q_c, Btu/sq ft/mo	P_s	ϱ	Q_{LS}, Btu/mo
Oct	2.6×10^8	4.7×10^4	9.04	.99	2.6×10^8
Nov	8.4×10^8	3.8×10^4	2.26	.59	5.0×10^8
Dec	12.9×10^8	3.5×10^4	1.36	.39	5.0×10^8
Jan	20.5×10^8	4.0×10^4	.98	.29	5.9×10^8
Feb	19.1×10^8	4.5×10^4	1.18	.35	6.7×10^8
Mar	16.9×10^8	4.9×10^4	1.45	.41	6.9×10^8
Apr	13.5×10^8	4.4×10^4	1.63	.45	6.1×10^8
May	9.4×10^8	4.9×10^4	2.67	.65	6.1×10^8
Jun	4.6×10^8	4.8×10^4	5.22	.97	4.5×10^8
					48.8×10^8 Btu

Step 3

To compute the cost of auxiliary fuel for the solar system, Q_{LA} must be determined from monthly Q_L and Q_c data. The values for Q_L and Q_c for the heating months are given in Example 3, Chapter 3. This information (along with an assumed collector area) allows calculation of a P_s for each month. The universal curve for heating (Figure 3) then gives the ϱ for each P_s. Finally a monthly Q_{LS} can be figured (ϱQ_L) and summed to get a yearly Q_{LS}.

Table B3 summarizes the procedure using the Q_L and Q_c from Example 3 of Chapter 3, with a collector area of 5×10^4. The Q_{LA} can be determined from

$$Q_{LA} = Q_L - Q_{LS} = 108 \times 10^8 - 49 \times 10^8$$

$$Q_{LA} = 59 \times 10^8 \text{ Btu/yr}$$

The solar auxiliary fuel cost, F_s, is given (assuming a boiler efficiency of .75) by

$$F_s = (59 \times 108 \text{ Btu/yr})\ (1/.75)(\$.5/\text{gal})$$

$$(1 \text{ gal}/1.5 \times 10^5 \text{ Btu})$$

$$F_s = \$2.7 \times 10^4/\text{yr}$$

Hence,

$$LO_s = MF_x = (42.4)\ (2.7 \times 10^4)$$

$$LO_s = \$1.13 \times 10^6$$

Step 4

Determine LCC, where

$$LCC = CC + LO_s - LO_c$$

for an A_c of 5×10^4 sq ft

$$CC = 2.05\ (3 \times 10^3 + 9.18\ A_c)$$

$$= 2.05[3 \times 10^3 + 9.18(5 \times 10^4)] = \$9.47 \times 10^5$$

Thus,

$$LCC = \$9.47 \times 10^6 + \$1.13 \times 10^6 - 2.04 \times 10^6$$

$$LCC = \$.037 \times 10^6$$

for a collector area of 50,000 sq ft. Once again, the value is small when compared to the capital and fuel life-cycle costs. The price of the solar energy system compares favorably to the cost of the conventional system.

Table B4 shows results of the analysis for other collector areas. The solar system of maximum cost benefit is seen to occur at a collector area of roughly 25,000 sq ft. At this point the computer simulation program should be consulted for a more exact analysis.

Table B4

Life-Cycle Costs for Various Collector Areas

Collector Area (sq ft)	LCC ($)
0	$+.6 \times 10^4$
10,000	-3.6×10^4
25,000	-5.3×10^4
40,000	-2.1×10^4
50,000	$+3.7 \times 10^4$
75,000	$+3+1.9 \times 10^5$

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